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Animal Feeds and Additives

Edited by Figen Kırkpınar and Zümrüt Açıkgöz

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Aims and Scope of the Series

Paralleling similar advances in the medical field, astounding advances occurred in Veterinary Medicine and Science in recent decades. These advances have helped foster better support for animal health, more humane animal production, and a better understanding of the physiology of endangered species to improve the assisted reproductive technologies or the pathogenesis of certain diseases, where animals can be used as models for human diseases (like cancer, degenerative diseases or fertility), and even as a guarantee of public health. Bridging Human, Animal, and Environmental health, the holistic and integrative "One Health" concept intimately associates the developments within those fields, projecting its advancements into practice. This book series aims to tackle various animal-related medicine and sciences fields, providing thematic volumes consisting of high-quality significant research directed to researchers and postgraduates. It aims to give us a glimpse into the new accomplishments in the Veterinary Medicine and Science field. By addressing hot topics in veterinary sciences, we aim to gather authoritative texts within each issue of this series, providing in-depth overviews and analysis for graduates, academics, and practitioners and foreseeing a deeper understanding of the subject. Forthcoming texts, written and edited by experienced researchers from both industry and academia, will also discuss scientific challenges faced today in Veterinary Medicine and Science. In brief, we hope that books in this series will provide accessible references for those interested or working in this field and encourage learning in a range of different topics.

Meet the Series Editor

With more than 35 years of academic experience, Dr. Rita Payan-Carreira is now a Full Professor at the University of Évora (UÉ). She specializes in animal theriogenology, with a particular focus on the determinants of female fertility and fetal-maternal interaction during implantation. Dr. Payan-Carreira is dedicated to promoting a culture of collaboration and knowledge-sharing within the scientific community. In addition to her extensive publication record, she frequently collaborates with various publishing houses on peer-review activities. She further contributes to the scientific advancement of students and professionals by supervising academic theses and offering technical and scientific courses, including scientific communication, critical reasoning and discussion, and the ethical aspects of research.

Meet the Volume Editors

Professor Dr. Figen Kırkpınar graduated from the Department of Animal Science at the Faculty of Agriculture, Ege University, İzmir, Türkiye in 1984. She was then assigned as a research assistant in the same department in 1986. She completed her Master of Science degree in 1987 and her Doctor of Philosophy degree in 1993, both at Ege University in Türkiye. She has received the 'National Publication Encouragement Award' from the Scientific and Technological Research Council of Türkiye and the Science and Technology Centre of Ege University seven times. In 2002, her project received an honourable mention at the Engineering Science Project Competition organised by the Science and Technology Centre of Ege University. In 2020, she was awarded an accolade from Ege University in recognition of her accomplishment in successfully completing the most scientific projects. She served as Head of the Animal Science Department from 2014 to 2017 and as Head of the Feeds and Animal Nutrition Department from 2011 to 2017. She served as a member of the Advisory and Executive Boards of the Scientific and Technological Research Council of Türkiye, as well as the Research Support Programs Directorate and the Agriculture, Forestry, and Veterinary Research Support Group, from 2017 to 2020. She also served as Deputy Director of the Application and Research Centre for Laboratory Animals at Ege University from 2017 to 2024. She has been a member of the Animal Experiments Ethics Committee at Ege University since 2013 and has served as vice president of the Farm Animal Experiments Ethics Committee since 2020. She has been Head of the Animal Nutrition Science Department since 2023. She has occupied the positions of Director of the Application and Research Centre for Laboratory Animals and Chairman of the Local Ethics Committee for Aquatic Vertebrate Experiments at Ege University since 2025. She has contributed to the editorial boards of scientific periodicals and has served as a peer reviewer. Professor Dr. Kırkpınar has authored or co-authored fourteen book chapters and over 200 research papers that have been published in peer-reviewed scientific journals and conference proceedings. The primary focus of her research endeavours pertains to the domain of feeds and animal nutrition, with a particular emphasis on feed additives, sustainable poultry nutrition, biotechnology, and the quality of meat and eggs.

Professor Dr. Zümrüt Açıkgöz graduated from the Department of Animal Science at the Faculty of Agriculture, Ege University, İzmir, Türkiye, in 1991. She was then assigned as a research assistant in the same department in 1993. She completed her MSc in 1995 and her Ph.D. in 1999, both at Ege University in Türkiye. She received the 'National Publication Encouragement Reward' from the Scientific and Technological Research Council of Türkiye four times. She was the vice chair of the Department of Animal Science from 2014 to 2017, and has been the chair of the Department of Feeds and Animal Nutrition since 2020. She has served as an editorial board member and acts as a referee for several scientific journals. Prof. Dr. Z. Açıkgöz is the author or co-author of one book and seven book chapters. Furthermore, she has had more than 120 research papers published in peer-reviewed scientific journals and conference proceedings. Her primary research areas include animal nutrition and feeds, with a focus on poultry nutrition, feed additives, and the quality of meat and eggs.

Contents

Preface

The global livestock industry currently finds itself at a critical juncture, facing significant challenges and decisions regarding innovation, sustainability, and responsibility. As populations increase and demand for animal products rises, the role of animal nutrition has become more critical than ever. Feed is not merely a means of sustenance for animals; it is a key driver of animal health, productivity, product quality, and environmental impact.

This book, *Animal Feeds and Additives*, was conceived to provide a comprehensive and up-to-date resource on the complex and evolving field of animal feeding. It brings together a range of topics essential to understanding both the science and application of modern feed strategies. From conventional ingredients and alternative feedstuffs to functional additives, microbiome modulation, and precision nutrition technologies, each chapter has been carefully developed to bridge the gap between research, innovation, and practical implementation.

The impetus behind preparing this volume was to devise a tool that is not only academically rigorous but also accessible and applicable to professionals in the field. The present volume is intended for a wide readership, including researchers, nutritionists, veterinarians, students, and experts in the feed industry. It is hoped that the book will offer new insights and inspire further inquiry.

In addition, contemporary challenges are addressed, including the development of antibiotic alternatives, the implementation of circular feeding models utilising food waste, and the sustainability of feed production. The objective of this initiative is to contribute to the global discourse on the potential for the evolution of animal agriculture to meet future demands in a manner that respects environmental and ethical boundaries.

We extend our sincere gratitude to the contributors, reviewers, and colleagues whose expertise and dedication made this work possible. We hope that *Animal Feeds and Additives* will serve as both a reference and a catalyst for continued progress in animal nutrition science.

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Chapter 1

Introductory Chapter: Recent Advances in Animal Feeding and Nutrition

Figen Kırkpınar

1. Introduction

Projections indicate that the global population will reach 10 billion by the year 2050. Concurrently, a surge in demand for food is projected, with estimations ranging from 35 to 56% [1]. This prediction is confirmed in the United Nations' 'World Population Prospects 2019′ report, which estimates that the world population will increase by approximately 2 billion in 30 years and that rapid population growth will lead to changes in food production and consumption all over the world due to globalisation, urbanisation and economic pressures [2]. Moreover, there is an anticipated escalation in the demand for the more efficient production of plants and animals in relation to water, energy, land and nutrients, in order to satisfy consumers' demands for safe and sustainable food. The significance of animal production lies in its contribution to our daily caloric and protein intake, which stands at 17 and 33% respectively. Furthermore, it facilitates the conversion of waste and by-products into high-quality animal protein sources, including milk, eggs and meat. Additionally, it plays a crucial role in utilising land that is not suitable for plant production and maintains a traditional function in various contexts [3, 4]. However, intensive animal production, while meeting the food needs of billions of people, also has negative environmental impacts, including land degradation, water pollution and increased carbon emissions. Moreover, the consequences of intensive animal production, including augmented environmental footprints and the diminution of biodiversity, have substantial negative effects [5, 6]. In such instances, it is imperative to adopt safe, high-quality and environmentally friendly production methods. The 'Sustainable Development 2030′ project, which is supported by UNESCO, emphasises the necessity of sustainable production [7]. The increasing enforcement of European legal frameworks regarding food safety and animal welfare has also led to growing interest in sustainable animal production.

The concept of sustainability is currently defined by the United States' National Agricultural Research, Publication and Education Policy Act of 1977 as a production method that prioritises sustainable economic, environmental and social efficiency, providing opportunities for future generations. It is imperative that enterprises engaged in intensive animal production ensure social, environmental and economic sustainability, particularly those that depend on external resources for animal nutrition [8, 9]. While energy consumption on farms and greenhouse gas emissions from animal shelters are recognised as environmental pollutants, primary factors such as feed production and raw material dependency are also

significant in limiting sustainability in animal production, particularly in the context of poultry enterprises [10]. While a plethora of criteria exist for environmentally friendly animal production in agriculture, including breeding, welfare and health, animal nutrition is considered the most significant factor. It has been determined that this cost constitutes 60-80% of operating costs and directly affects production performance, animal health, the environmental footprint of animal products and animal welfare [11].

The livestock sector is responsible for 14.5% of human-induced greenhouse gas emissions, with emissions of 7.1 gigatonnes of CO2-eq per annum. Beef and cattle milk production account for the majority of these emissions, at 41% and 20%, respectively. Pork meat and poultry meat and eggs contribute to 9% and 8% respectively. Projections show that this production will increase, leading to higher emissions. The main sources of emissions are feed production and processing (45%) and enteric fermentation from ruminants (39%). Manure storage and processing account for 10%. The remainder is due to the processing and transportation of animal products. Expansion of pasture and feed crops into forests contributes to about 9% of the sector's emissions. Finally, fossil fuel consumption along the sector supply chains accounts for about 20% of sector emissions [12]. It is recommended that technological processes, breeding and feeding strategies be developed to reduce greenhouse gas emission production. In order to address this issue, feeding strategies are being implemented, including the use of high-quality forages, additives (probiotics, prebiotics, organic acids and secondary metabolites) and fat supplementation [13, 14]. Ruminants generally require extensive grazing land, resulting in increased global greenhouse gas emissions due to changes in land use and enteric fermentation. Poultry farms have exhibited an increasing trend over the last 30 years, thus occupying a significant place among global industries, with their short production cycles and rapid returns on capital. It is acknowledged that each phase of poultry production, encompassing raw material processing, feed production and manure management, exerts a discernible environmental influence [15, 16]. The utilisation of imported protein sources, particularly soy, has been demonstrated to exert a detrimental effect on sustainability [10]. These detrimental effects can be mitigated through the implementation of appropriate feeding strategies, genetic research and breeding studies, with the overarching aim of achieving environmentally sustainable production practices. It is acknowledged that the resources exerting the most significant influence on the natural environment in intensive poultry production are those associated with feed production and manure management, which are inextricably linked to nutrition [15–17]. The formulation of strategies to reduce these resources must be approached with meticulous planning and development. The feeding strategies employed in the context of sustainability in poultry production are predicated on the impact of feed production, nutrient excretion and the digestive system.

In recent years, a number of feeding strategies have been developed with the aim of reducing the environmental footprint. One such approach involves the adoption of the 'Life Cycle Assessment' concept, with the objective of mitigating the environmental impact of feed production processes. The objective of this methodology is twofold: firstly, to satisfy nutritional requirements and formulate an economical mixed feed, and secondly, to consider the environmental impact [18, 19].

An alternative feeding strategy that has been employed is the evaluation of alternative feed sources. The primary objective is to enhance the utilisation of alternative feed ingredients, with the aim of substituting animal protein sources and soy. It has been established that hydroponic systems, a model of soilless farming, have the capacity to reduce the environmental impact of feed production.

In order to reduce nutrient excretion, feeding strategies that increase nutrient digestibility are being implemented. These include reducing crude protein levels, adding crude fibre and using biotechnological applications in raw materials and feed additives [20, 21]. In recent years, the relationship between digestive system health, production performance and environmental impact in poultry has been the focus of much attention. Recent developments in animal feeding and nutrition can be examined under several headings.

2. Alternative feed ingredients

The growing global demand for animal protein, coupled with the rising cost and limited availability of traditional feed ingredients such as corn and soybean meal, has prompted researchers and the livestock industry to explore alternative feed ingredients. These alternatives aim to reduce dependency on conventional feedstuffs, lower feed costs, promote sustainability and minimise competition with human food chains. The major categories of alternative feed ingredients are:

- Agricultural and agro-industrial by-products: Examples include wheat bran, rice bran, sugar beet pulp and oilseed cakes.
- Food waste and kitchen residues: This includes bakery waste and vegetable trimmings.
- Insects and insect meals: Insect-based feeds like black soldier fly larvae, mealworm.
- Aquatic sources: Alternatives such as algae and fish silage.
- Novel plant-based ingredients: Duckweed, moringa and lupin.
- Microbial and fermentation products: Single-cell proteins and fermented feeds offer sustainable protein sources.
- Soil-free produced feed ingredients: hydroponic, aeroponics and aquaponic feeds.

In animal husbandry, feed costs constitute 60–80% of operating expenses and are therefore crucial for environmentally friendly, sustainable and economical production [11]. Currently, plant proteins are the primary source of protein in animal nutrition. However, imported protein sources, especially soy, can have a negative impact on environmentally friendly and sustainable production [10]. It has been reported that sustainable and environmentally friendly animal production can be achieved by using by-products from other industries, locally sourced feeds and invertebrates such as insects, worms and algae as alternative protein sources in animal nutrition [15, 17]. Corn, wheat and barley are the most commonly used energy feeds in animal feed. There have been several reasons for the rise in popularity of by-products and waste as animal feed: pollution abatement, regulations, waste disposal costs and changing perceptions of their value as feed alternatives. The main drivers are reducing feed costs and using during droughts or when fibre-rich forages are limited. By-products come

from various agro-industrial sources and market sources such as fruit and vegetable waste. Livestock is one of the fastest-growing agricultural sectors, especially in developing countries. However, many developing countries have feed deficits. Alternative feed sources such as by-products, fruits, vegetables and crop residue-derived feeds could help to address these issues [22]. They could also be cost effective and beneficial to producers.

It is vital to use resources most efficiently and evaluate the least wasteful foods. We need to promote alternative feed materials to increase species productivity and reduce food competition between humans and animals. About 30% of food is wasted before it reaches people, and this figure is increasing [23]. So, we need to manage our waste more sustainably.

According to Lassaletta et al. [15], 33% of the world's arable land is used to produce feed raw materials. Land scarcity and high production costs are the main reasons why forage crop cultivation areas are not expanding more. Climate change means we need more plants that can tolerate poor soil conditions and require less water. So it is crucial to support forage crops and increase the profitability of livestock farming to ensure sustainable production. Supporting forage crops and increasing livestock profitability are crucial for sustainable production. Drought and climate change have a big impact on grain, legume and forage crop production. Global warming is also affecting pasture and rangeland yields, which has a negative impact on livestock farming. So it is important to develop and breed varieties of forage crop seed that can withstand climate change, drought and cold and to increase the use of disease-resistant varieties [24].

Soilless farming systems aim to produce crops without excessive fertiliser and pesticide use, significantly increasing crop yields and allowing more efficient water use [25]. These systems are the best alternative for sustainable and environmentally friendly production, minimising negative impacts while increasing production capacity and agricultural income. Soilless farming models permit year-round plant production, independent of environmental conditions. Smart technologies allow remote control of the systems. Plants can be grown in much shorter times compared to traditional farming, yielding higher quality and quantity. Less water and fertiliser are required, resulting in environmentally friendly production. Because plant pests, diseases and weeds are less common, pesticide use is eliminated.

Alternative feed ingredients hold significant potential to transform the future of animal nutrition, making it more sustainable, efficient and resilient. Continued research, feed safety regulations and technological advancements will be critical to integrate these ingredients effectively into mainstream livestock diets.

In recent years, one of the feeding strategies adopted to reduce the environmental footprint of sustainable animal production is the use of the 'Life Cycle Assessment' concept to minimise the environmental impact of feed and raw material production when preparing compound feeds. This method aims to meet nutrient needs, create economical compound feed and consider the environmental footprint [18, 19]. On the other hand, increasing feed utilisation is also important. Considering the suitability and efficient use of production systems and identifying the relationship between each feed and farming systems will contribute to improving self-sufficiency.

It is important to increase feed utilisation. The suitability and effective use of production systems must be taken into account and identifying each feed and its use in relation to the farming systems is conducive to cultivating self-reliance.

3. Use of functional feed additives and nutritional modulation of the microbiome

Functional feed additives are included in animal diets to enhance performance, health, feed efficiency and product quality. These additives provide physiological and immunological benefits that go beyond basic nutrition, supporting sustainable livestock production in the face of increasing regulatory restrictions on antibiotic use. In modern animal production systems, the demand for sustainable and efficient livestock production has prompted the increased use of functional feed additives. Unlike traditional additives that primarily provide nutrients or preserve feed, functional additives confer additional health and performance benefits by modulating immune responses, improving gut health, enhancing nutrient absorption and mitigating environmental impacts [26]. The incorporation of functional feed additives into animal nutrition represents a critical innovation for sustainable livestock production. Their ability to enhance growth performance, immune function, gut health and nutrient utilisation makes them essential tools in antibiotic-free and environmentally friendly production systems. As research advances, the development of more targeted and synergistic additives will continue to improve animal welfare and productivity.

There is growing interest in natural feed additives as alternatives to antibiotics and synthetic growth promoters. These include: phytogenics (essential oils, herbs and spices), biotics (probiotics, prebiotics, symbiotics, postbiotics and parabiotics), organic acids, functional amino acids, enzymes and mycotoxin binders.

Functional feed additives exert their benefits through several mechanisms: modulation of the gut microbiota to favour beneficial bacteria, stimulation of the immune system to improve disease resistance, enhancing nutrient digestibility *via* enzymatic or microbial action, reduction of oxidative stress by boosting antioxidant activity, reduction of pathogenic load and contributing to lower antibiotic use.

Functional feed additives will continue to gain prominence as part of integrated health management systems. Future developments may focus on precision delivery, synergistic combinations and data-driven formulation based on microbiome and metabolome profiles. Alternative feed ingredients offer a sustainable and resilient solution for animal nutrition. Research, safety standards and innovation will drive their future adoption.

4. Precision nutrition and digital technologies

Precision nutrition aims to match dietary supply with the exact nutritional needs of animals, taking into account genetic background, physiological stage, environmental conditions and health status [21]. This minimises nutrient excretion, improves feed efficiency and reduces feed costs. Adoption of new technology is vital to manage greenhouse gas emissions, find sustainable protein sources and better utilise grassland. Omics technologies will improve understanding of how the rumen affects animal productivity and efficiency and of foetal programming. Precision farming technologies will enable better management decisions, mitigate disease and improve livestock welfare and genetics. Producers who implement business plans using this technology will be able to meet the needs of a hungry global population [27].

Precision nutrition, integrated with digital technologies, represents a transformative approach in animal production systems. In recent years, livestock production has faced increasing pressure to become more efficient, environmentally sustainable

and responsive to animal welfare. Precision nutrition, defined as the precise supply of nutrients to meet individual animal requirements, has emerged as a solution to optimise feed utilisation and productivity [27]. When combined with digital technologies, this approach holds great promise for the future of animal agriculture.

Precision nutrition is a key part of this and involves supplying the right amount of feed to animals at the right times. This needs automatic data collection and control. There are challenges to precision nutrition's success, but the benefits for producers are great. The most suitable sensors must be used and developers should concentrate on identifying the relevant information needed for precision nutrition to function optimally. This can be achieved by using feedback control algorithms to automatically determine the best nutrient supply. Mathematical models are the preferred way to process data, but these must be designed to operate in real time. Combining knowledge-based and data-driven models using machine learning enhances our ability to use farm data, opening up new opportunities for precision nutrition [28]. Precision nutrition supported by digital technologies is redefining animal feeding strategies. Continued innovation, combined with farmer training and infrastructure support, will determine its successful implementation in future animal production systems. Precision nutrition provides animals with nutritional support based on their characteristics and stages. In the agricultural and livestock industry, precision nutrition is applied in several key areas:

- Feed formula optimisation: Factors such as species, age, gender, growth stage and production performance are used to design feed formulas. These enhance feed utilisation efficiency and reduce costs.

- Nutritional requirement assessment: Biotechnology and information technology enable precise evaluations of animals' nutritional needs. This improves animal health and productivity.

- Feeding strategy development: Scientific feeding strategies are formulated based on feeding behaviours. Techniques such as phase feeding and time-restricted feeding improve digestion and the efficiency of nutrient absorption.

- Online nutrition management systems: Large feed manufacturers use online animal nutrition management systems. These systems integrate smart equipment. This ensures precise production of feed and real-time nutritional adjustments.

- Smart tech plays an integral role in precision nutrition by using data and automation. Precision nutrition means giving animals the right food at the right time to help them grow & perform.

It covers:

- Optimising feeds to save costs and be more efficient

- Checking animals' nutritional needs with tech to improve health and productivity

- Coming up with feeding strategies based on how they eat and digest

- Online systems for managing animal nutrition

5. Conclusion

Animal products play a vital role in providing nutritious food for the human population. In light of the growing demand for animal protein, it is crucial that the sector achieves environmentally, economically and socially sustainable production methods.

Sustainable animal production must be considered from environmental, economic and social perspectives. This can be achieved by minimising the environmental impact of feed production, reducing nutrient excretion and improving digestive systems. Recommended strategies to reduce fertiliser and nutrient excretion and emissions include precision feeding, reducing crude protein levels, adding crude fibre, using feed additives and technological processes. Strategies such as Life Cycle Assessment techniques, alternative protein sources and soilless farming models can reduce the environmental impact of feed ingredients.

Livestock production faces challenges: competition for feed, shortage of high-quality feeds, greenhouse gas emissions, pollution, feed safety, demand for better-quality animal-origin safe foods, antibiotic-resistant human pathogens, animal health and welfare. These will only worsen in future. Animal feeding and nutrition will be key in solving these challenges. New feed resources, including valorisation of biowastes and vegetable, fruit processing by-products as animal feeds, must replace human-edible feeds and improve dietary quality. Proper feeding management can reduce greenhouse gas emissions and environmental pollution, enrich health-promoting bioactive principles in animal-derived foods, improve animal health and welfare.

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Chapter 2

Current Situation, Future Goals, and Strategies of the Global Feed and Feed Additives Industries

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Abstract

As the world's largest land users, livestock occupy one-third of the world's ice-free land surface for grazing and one-quarter of arable land for feed production. This sector is a critical part of the overall agricultural economy and generates nearly 40% of global agricultural gross domestic product. As a result of population and economic growth plus urbanization, the demand for livestock products is growing rapidly. By 2050, the global demand for animal products will increase by 60–70%, although with differences between all regions. The livestock sector can meet future demand by increasing the number of animals and improving productivity. Increasing animal numbers will clearly add to this demand for feed. However, additional feed production will increase greenhouse gas emissions from the livestock sector. Moreover, food insecurity will be further exacerbated if additional feed needs are met by food grains. Under these circumstances, it is extremely important to increase livestock productivity through scientific and technological developments to meet public demand for animal products. Feed additives are minor but important ingredients in animal nutrition. In different livestock species, feed additives (amino acids, vitamins, minerals, antioxidants, enzymes, herbs, organic acids, biotics, etc.) may influence feed quality, feed producing, feed utilization, animal health, performance, products quality, production cost, and environmental emissions. The global feed additives market size was valued at USD 37.92 billion in 2024. In the future, the feed additives market will grow according to the demand and preference for animal products. In this book's chapter, the current status, future goals, and strategies of the global feed and feed additives industries are informed.

Keywords: livestock, feeds, additives, climate change, sustainability

1. Introduction

Livestock systems are rapidly evolving in relation to various drivers. Human population growth at 9.4–10.1 billion [1], urbanization at 68% [2], and growing incomes at 2% in developed countries and 3.3% in low- and middle-income countries [3] projections by 2050 will lead to considerable increases in the demand for livestock products

in the future. Global demand for animal meat and milk is predicted to increase by 57 and 48%, respectively, between 2005 and 2050 [4]. This demand will trigger the animal population growth from over 60 billion to 100 billion by 2050 [5]. Meeting feed required by this animal population may put substantial pressure on a wide range of natural resources such as land and water, and exacerbate climatic change and variability.

As the world's largest land users, livestock occupy one-third of the world's ice-free land surface for grazing and one-quarter of cropland for feed production [6]. The rapid growth of the livestock sector has led to environmental degradation through overgrazing, deforestation, and greenhouse gas (GHG) emissions [7].

The growing demand for food and animal feed imposes a high pressure on the land use and can continuously generate more gas emissions, which harm the environment. Global feed demand is projected to nearly double to feed animal population by 2050 compared to the year 2000. For example in 2004, 690 million tonnes of cereals, 18 million tonnes of oilseeds, and 295 million tonnes of protein-rich processing by-products were fed to livestock. Over 1.3 billion tonnes of cereal grains will be consumed by farm animals each year by 2050 [5].

Feeding animals with soybean, other oilseeds, and cereals grains is currently viewed as a direct competition against human food security, and on the other side it is not sustainable [8]. The price fluctuation and supply challenges on these raw materials have resulted from extreme weather conditions and impacts of the global COVID-19 Pandemic. The outcomes are; operational efficiency has suffered, uncertainty has grown, and firms have lost a lot of money [9]. Furthermore, 14% of the world's agricultural land, representing 50% of the world's arable land, is pressured to convert to cropland [10]. Therefore, substitute feeds and protein supplements or even feed additives are definitely needed to replace the current supply and meet the growing demand.

The future hope of feeding animals and safeguarding their food security will depend on the better utilization of unconventional feed resources. Non-conventional feeds can partially fill the gap in the feed supply, reduce the competition for food grains among humans and animals, reduce feed costs, and contribute to the self-sufficiency of nutrients from local feed resources [11]. The most popular non-conventional feedstuffs are agro-industrial by-products. These include by-products from flour milling, sugar factories, edible oil processing factories, breweries, and abattoirs. Some of the constraints of unconventional feedstuffs include; low nutritive value, high moisture content, and presence of anti-nutritional factors [12].

In order to feed over 9 billion people in the world by 2050, farmers will need to produce relatively inexpensive high-quality products using raw materials that do not compete with humans [13]. Considering low quality of the uncoventional feedstuffs, it is strongly recommended to formulate them with feed additives to maximize their utilization [14]. Feed additives are products that improve the quality of feed and the quality of animal products. Additives also improve the animals' performance and health. For instance, a feed containing functional feed additives promotes the growth and health of animal, improves their immune systems, and induces physiological benefits beyond traditional feeds [15, 16].

Over the past decades, the animal feed industry has seen a tremendous growth through advanced formulation practices, improved processing technologies, consistency in quality control of the feed ingredients and finished products, new developments in the use of the feed additives and supplements for efficiency, and innovations

in the search of novel or alternative feedstuffs. This chapter book will discuss the current status, future goals, and strategies of the global feed and feed additives industries.

2. Global status of animal feed production

Feed production is the main contributor to the environmental and economic impacts associated with livestock production systems worldwide. It is predicted the global feed demand to be almost doubled (1.8–2.3 times) by 2050 compared to 2000 [17]. Global livestock production systems rely largely on unsustainable feedstuffs of plant origin to cover the needs for protein required in livestock nutrition [18]. Animal feed production is in direct competition for resources required to produce human food, particularly as a result of increased demand for animal products, population growth, and adverse effect of climatic change.

Cropland occupies one-third (1.6 billion hectares) of the total agricultural land, and the remaining two-thirds are permanent meadows and pastures for livestock (3.2 billion hectares) [19]. It has also been reported that 33% of croplands are used for livestock feed and fodder production. About one-third of the world's cereal production is fed to animals. Livestock decreases food supply, since the grains used for human consumption are fed to animals, especially monogastric animals. Approximately one-third of the world's cereal production is fed to animals [8].

Maize is a major global and versatile cereal that is growingly playing a key role in global agri-food systems. Today, maize is mainly used as an animal feed globally; 56.3% for feed, 12.8% for food, and 19.1% for other uses. Maize production has increased by 118% between 1995 and 2019. This production is propelled by rising demand by the feed industry, a combination of yield increases, and area expansion by 46% during the same period. This cereal already has the highest production volume and is expected to be the most widely cultivated crop in terms of area in the coming years. Generally, cereal production area and yield considerably increased over the past decades [20].

Soybean production has seen a tremendous growth over recent years due to its importance in the food and feed industries. Soybean is currently ranked sixth in production volume, and fourth in both production area and economic value, making it one of the most widely grown crops in the world [21]. The soybean market has grown at a compound annual growth rate (CAGR) of 4.2% between 2019 and 2024 and is projected to reach a CAGR of 5.9% from 2025 to 2032 [22]. According to the United States Department of Agriculture (USDA), 87% of the global soybean output is used for oil and meal production. This high-protein meal accounts for approximately 70% of global protein meal production and is an important feed component, especially for poultry and pigs. The growth of soybean production is primarily driven by the increasing demand of soybean meal for animal feed, and hence by the growing demand for animal-based products [21].

The feed industry has experienced average annual growth of 3 and 3.7% over the last ten and five years, respectively. Total feed production decreased by 0.01% in 2023 (1295.28 million metric tonnes (MMT)) compared to 2022 (1.295.42 million metric tonnes) (**Table 1**). In both years, the highest feed production was recorded in the broiler and pig sectors (**Table 2**). The slight decline in feed demand was partly due to the more efficient use of feed made possible by intensive production systems that focus on the use

Region	2023 feed tonnage (MMT)	2022 feed tonnage (MMT)	Growth (MMT)	Growth (%)
Asia-Pacific	475.33	468.79	6.54	1.40%
Europe	261.89	269.48	−7.59	−2.82%
North America	259.26	262.06	−2.80	−1.07%
Latin America	200.67	198.21	2.457	1.24%
Africa	51.42	50.44	0.98	1.94%
Middle East	35.93	36.05	−0.12	−0.32%
Oceania	10.78	10.40	0.39	3.71%
Total	**1295.28**	**1.295.42**	**−0.14**	**−0.01%**

MMT: million metric tonnes.

Table 1.
2022 and 2023 global compound feed production by region.

Sector	2023 feed tonnage (MMT*)	2022 feed tonnage (MMT)	Growth (MMT)	Growth (%)
Broiler	386.33	373.52	12.81	3.4%
Pig	323.04	327.17	−4.14	−1.3%
Layer	171.293	171.292	0.01	0.0%
Dairy	127.92	129.38	−1.45	−1.1%
Beef	119.56	124.26	−4.70	−3.8%
Aqua	52.09	54.49	−2.40	−4.4%
Pet	35.44	34.52	0.92	2.7%
Equine	7.98	8.37	−0.39	−4.69%
Totals*	**1295.276**	**1295.416**	**−0.14**	**−0.01%**

*MMT: million metric tonnes. *Includes other ruminants, other poultry, turkey, and calf sector data.*

Table 2.
2022 and 2023 global compound feed production by sector.

of animal nutrition, farm management, and other technologies to reduce feed consumption while producing the same amount of protein, or more. The slowdown in animal protein production in response to tight margins experienced by many feed and animal protein companies also contributed to the small decline in feed demand. Changing consumption patterns driven by inflation and dietary trends, higher production costs, and geopolitical tensions also impacted feed production in 2023 [23].

Feed industry will grow much more in the coming years and its sustainability will depend on the ability to explore and exploit new feed ingredients that are human inedible. Prompt search for alternative feedstuffs that do not compete with crops for land is also imperative. Therefore, it is important to consider the potential environmental, economic, and social impacts of such alternatives to ensure the efficacy, viability, and sustainability of animal feed, as well as to assure food safety and protect human health [24].

3. Common alternative feedstuffs used in animal nutrition

The need for alternative feedstuffs is highly influenced by societal demands. On the other hand, there is a need for a more circular economy with less waste and

environmental impacts due to the reuse of all products. Therefore, it is necessary for the feed industry to exploit leftovers of human food and by-products of human food processing and made available as livestock feed. Many of these by-products from food industries are already reused nowadays, but there is much to improve for human food leftovers. While by-products of food production are often of lower feeding quality, they may be available at relatively lower cost [25]. On the other hand, there is a need to improve production and enhance the use of genetically modified crops and novel protein sources (insects, algae, etc.) in livestock nutrition.

3.1 Algae

Algae, photosynthetic organisms, live in water or moist places. They are divided into two groups according to their size: microalgae or phytoplankton, which are microscopic single cells, and macroalgae or seaweeds, which are macroscopic multicellular organisms visible to the naked eye [26, 27]. They have recently attracted considerable attention due to their rapid growth potential, high biomass production, low environmental impact, and non-competition with crops for arable land and fresh water [28]. Algae are also rich in nutrients and bioactive compounds [29, 30], and their nutritional composition varies between and within species according to growth conditions [31, 32]. Microalgae have all essential amino acids, and some of them are rich in protein and lipid. Many marine species produce n-3 long-chain polyunsaturated fatty acids, such as eicosapentaenoic acid (EPA; C20:5 n-3) and docosahexaenoic acid (DHA; C22:6 n-3), which have important health benefits [33]. Conversely, macroalgae have highly variable protein content and quality, especially low in brown macroalgae, and low lipid fractions, although marine species have a relatively high content of long-chain polyunsaturated fatty acids [32]. Both groups of algae are good sources of complex structural carbohydrates, natural pigments, and organic minerals with important health-promoting qualities due to their prebiotic, immunomodulatory, and antioxidant activities [29, 30, 34, 35].

Nowadays, algae are favored in many commercial applications (food, feed, cosmetics, pharmaceuticals, bioenergy, biofuels, etc.). Due to their nutritional and functional properties, algae have the potential to be used as natural feed and feed additives. Algae have been the subject of several animal studies. They have produced conflicting results due to differences in dose, species, and experimental conditions. Meanwhile, algae, especially red seaweed (*Asparagopsis taxiformis* and *Asparagopsis armata*), show promise as a natural approach to reducing methane (CH_4) emissions from ruminants [36].

3.2 Insects

In recent years, there has been growing interest in insect-based feeds due to their high nutritional value and sustainability. Insects are natural decomposers and can be grown on bio-waste and organic side streams, thus contributing to the circular economy by transforming waste substrates into nutrient-rich resources (protein, fat, and some minerals). Furthermore, insect farming needs significantly less land and water, and emits fewer GHGs [37]. Despite these benefits, there are also challenges and limitations related to their use, including the need for large-scale insect production, legal regulatory frameworks, consumer acceptance, and ensuring consistent nutritional quality [38, 39].

Insects have a high-protein content, ranging from 20 to 76% of dry matter, depending on the species, stage of development, and substrate used for production [40]. The most common limiting amino acids are histidine, lysine, and tryptophan [41]. Insect meals also have high protein digestibility rates [42–44]. Therefore, they are recommended as an alternative to soybean and fish meals in fish, pig, and poultry feed. The European Commission allowed the use of insect meals as feed for fish farming in 2017 and for pigs and poultry sectors in 2021 [45]. The five insect species approved as feeds are the housefly (*Musca domestica*), the black soldier fly (*Hermetia illucens*), the mealworm (*Tenebrio molitor*), locusts (*Locusta migratoria, Schistocerca gregaria, Oxya species*), and silkworms (*Bombyx mori*) [46].

The insect-based feed industry is still relatively new. It is estimated that the global market potential for insect protein could reach up to half a million metric tonnes by 2030, of which 40, 14, 10, and 6% will be used in fish, broiler, layer, and pig feeds, respectively [47]. Meanwhile, the International Platform of Insects for Food and Feed (IPIFF) [48] estimates that the European insect sector's total production capacity could reach a million tonnes of insect meal by 2030 (i.e., including food-producing animals and other applications) under the right conditions (e.g., regulatory developments). It also reported that more than 10% of the fish consumed, 1 in 40 eggs consumed, 1 in 50 servings of chicken meat, and 1 in 100 servings of pig meat will be derived from insect-fed fish, laying hens, broilers, and pigs, respectively.

3.3 Single-cell protein

Single-cell protein can be used as protein supplements in feeds, especially in aquatic species and poultry. However, among many microorganisms that can produce protein, including bacteria and yeast, only a limited number of organisms have been exploited at a commercial scale. The single cells are able to use agricultural waste materials, such as rice straw, rice husks, manure, and starchy residue, as fermentation substrates and transform them into high-quality protein [49]. Besides their high protein content (between 60 and 82% of dry cell weight), single-cell proteins also contain other nutrients [50]. Yeasts are probably the most widely used single-cell protein [51]. *Candida*, *Hansenula*, *Pichia*, *Torulopsis*, and *Saccharomyces* are commonly used yeast species. As well as having many attractive qualities, single-cell proteins have limitations for animal nutrition, including low digestibility, presence of toxins, and high concentrations of nucleic acids [10].

4. Trends in the use of feed additives

Today, intensive livestock and fish production has made remarkable progress in efficiently and economically producing high-quality and safe milk, meat, eggs, and other products. At the same time, the industry has been able to maximize animal health and welfare and minimize the industry's impact on the environment. The use of feed additives has undoubtedly played a critical role in achieving this success. Feed additives are important components in feed production because they increase feed efficiency, provide essential nutrients, improve animal growth and health, and enhance feed palatability and metabolism.

The global feed additives market is expected to grow from $37.92 billion in 2024 to $53.66 billion in 2032, at a compound annual growth rate of 4.36% over the forecast

period. Asia-Pacific dominates the feed additives market with a market share of 38.13% in 2024. This can be attributed to the presence of China and India, which are among the top five countries in terms of animal feed production, which is expected to grow by more than 4% from 2021 levels [52].

Based on animal type, the global feed market is mainly segmented into cattle, poultry, swine, sheep, goats, and aqua feed. The poultry sector held the largest share in 2022 and is expected to maintain this leadership during the forecast period. The ever-growing poultry sector is expected to expand over the forecast period due to increasing demand for eggs and chicken meat. After the poultry sector, the animal feed industry is the second largest user of feed additives [52].

The animal feed additives market has been segmented into amino acids, vitamins, and minerals, antioxidants and others on the basis of the type of additives. Amino acids held the largest share of the feed additives market last year and this is expected to remain unchanged over the forecast period. The optimum balance of amino acids in the standard diet is important for achieving optimal productivity. L-methionine, L-valine, L-lysine, L-tryptophan, L-threonine, and L-arginine are the main amino acids added to the feed [52].

5. Common feed additives in animal farming

Antibiotics (as growth promoter) have been extensively used for enhancing poultry production but due to development of antimicrobial resistance and residual effects of these feed additives in eggs and meat, they lead to various health hazards to consumers [53]. As a result, the use of antibiotics as growth promoters in animal feed was banned in the European Union since January 2006. Therefore, natural alternatives with antibiotic-like effects have been sought.

The most prevalent feed additives used in the animal diets are antimicrobials, antioxidants, emulsifiers, toxin binders, colorant substances, probiotics, prebiotics and enzymes, organic acids, amino acids, and herbs. However, only feed additives that improve gut health and improve feed efficiency are discussed.

5.1 Biotics

Biotics are feed additives that have regulatory, protective, and activating properties on the microbiota. Probiotics, prebiotics, symbiotic, postbiotic, parabiotic, and other biotic substances are effective ways to promote a healthy gastrointestinal tract, immune system, and overall health of livestock.

Probiotics are live strains of strictly selected microorganisms that, when administered in adequate quantities, provide health benefits to the host [54]. They are a popular way to improve animal production performance, immune system, microbiota, overall health and welfare [55, 56]. Many different species and strains of probiotics (*Lactobacillus* spp., *Enterococcus* spp., *Bifidobacterium* spp., *Lactococcus* spp., *Pediococcus* spp., *Streptococcus* spp., *Leuconostoc* spp., *Weissella* spp., *Bacillus* spp., *Saccharomyces* spp., and *Candida* spp.) have different mechanisms of action. Today, probiotics are widely used not only in animal feeds, particularly in pig and poultry feeds, but also in ruminant feeds. Depending on the species and age of the animals, one or more selected probiotic microorganisms can be added to the feed or premix periodically or continuously in various forms (powder, suspension, capsule, pellet, gel, or paste) [57].

Prebiotics are defined as indigestible substrates that are selectively used by host microorganisms to provide health benefits by stimulating the growth and/or activity of beneficial bacteria of the genera *Lactobacillus* and *Bifidobacterium* in the gastrointestinal tract. These feed additives regulate the microbiota in the digestive system, promote the production of short-chain fatty acids, and increase nutrient absorption [58, 59]. Among the many prebiotics used in animal nutrition are inulin, fructooligosaccharides, galactooligosaccharides, and mannanoligosaccharides [60].

Symbiotics are defined as mixtures of probiotics and prebiotics that provide health benefits to the host by selectively stimulating the growth and/or activating the metabolic pathways of the health-promoting bacteria. Symbiotics have been shown to beneficially alter the composition of the gut microbiota and increase villus height and crypt depth in the intestinal mucosa [61]. They also have mechanisms of action, such as protection of the gut microbiota and activation of beneficial bacteria. The combined use of probiotics and prebiotics in animal nutrition has more favorable results in improving growth and production performance, the immune system, and the gut microbiota than their use alone. Care should be taken when selecting prebiotic and probiotic combinations for symbiotic use and preference should be given to combinations that have synergistic effects compared to the use of either product alone.

The fact that probiotic microorganisms are living and are significantly affected by the conditions in the production process presents some technological difficulties in their practical use. Recently, the production of postbiotics and parabiotics, which offer the same benefits, has come to the fore. Technologically, it is becoming increasingly important to use paraprobiotics and postbiotics instead of probiotics because they can be easily added to products that require high heat treatment during their production, there is no need for a cold chain as there is no problem of loss of viability, and they are easy to store, transport, and sell.

Postbiotics are defined as metabolite products synthesized by probiotic microorganisms during growth, reproduction, or fermentation and are predicted to have a similar mechanism of action to probiotics [62, 63]. They are defined as cell metabolites, biogenics, cell-free supernatant, functional proteins/enzymes, extracellular polysaccharides, teichoic acid, pili-type structures, metabiotics (microbiota metabolites), and metabolic wastes of probiotic activity [64, 65]. These metabolite-side compounds and/or products are considered to have similar mechanisms of action to probiotics [62, 63].

Parabiotics are defined as inactivated (non-living) microbial cells that provide benefit when administered in sufficient quantities [66]. Parabiotics can have positive effects on health through immune system modulation, inhibition of pathogens, and secretion of various metabolites [67, 68].

Biotics have long been used to promote animal health, but responses to treatment have been variable, so more experimental data are needed to move the field forward. Improving understanding of the complicated microbiota-host interactions involved will allow sound interpretation of experimental results, thus allowing the development of more effective biotics in the future.

5.2 Enzymes

Specific digestive enzymes are added to animal feeds to improve their nutritional value by increasing digestion efficiency. They are also used to support the breakdown of anti-nutritional factors, reduce the viscosity in the digestive tract, allow the use of cheaper feedstuffs, and reduce environmental risks related to manure and waste

disposal [69–71]. For animals, exogenous microbial enzymes improve nutrient utilization, optimize gut health, and enhance performance uniformity (e.g., daily growth rate, egg production, or milk production). For producers, they decrease feed costs and improve profitability.

The most common feed enzymes are phytases, xylanases, and β-glucanases (cellulases). Currently, the use of mannanases, α-galactosidases, pectinases, amylases, and proteases is increasing. The poultry and swine sectors are the major users of enzymes. However, the use of enzymes in ruminants, aquaculture, and pets is expected to increase in the forthcoming years [69].

5.3 Organic acids

Organic acids have antimicrobial activity and this effect is essentially the same, whether acting in feed or digestive tract. The most prominent mechanisms of organic acids are lowering the pH in the feed and gastrointestinal tract, increasing proteolytic enzyme activity, improving pancreatic secretions, stimulating the activity of digestive enzymes, inhibiting the growth of pathogens such as *Escherichia coli*, *Campylobacter* spp., and *Salmonella* spp., promoting the growth of beneficial bacteria, and increasing nutrient digestibility. They also act as an energy source during gastrointestinal tract intermediary metabolism. The most used organic acids as feed additives are lactic, formic, and propionic acids. In addition, the use of organic acid mixtures is recommended due to the synergistic effect between them [72].

5.4 Phytogenics

Aromatic plants and products derived from them (extracts, cold-pressed oils, and essential oils) have multifunctional properties (growth factor, digestive stimulant, immunomodulator, antimicrobial, antioxidant, anti-inflammatory, anti-stress, etc.) due to the bioactive compounds (flavonoids and polyphenols) in their structure [73, 74]. The use of herbal products in animal nutrition has increased due to the prohibition of antibiotics, and their growth stimulant effects have been examined. Phenolic compounds have growth-promoting properties; cause a decrease in the number of pathogenic bacteria, such as *E. coli, Clostridium perfringens, Salmonella typhimurium*, etc., in the intestinal lumen due to their antimicrobial properties, increase in the populations of beneficial bacteria such as *Lactobacillus* spp. *and Bifidobacteria*, etc., due to their prebiotic-like effect, improvements in intestinal morphology (absorption surface, villus:crypt ratio) due to antioxidant and anti-inflammatory properties, digestive secretions such as bile and mucus, and enzyme activities such as pepsin, trypsin, chymotrypsin, carboxypeptidase, lipase, and fermentation products such as nitrogen release [75–82]. In addition, plant extracts and essential oils have the potential to be used as rumen manipulation agents. They can increase total volatile fatty acid production by stimulating propionate and decrease methane production by reducing rumen methanogens [83–86].

5.5 Amino acids

Amino acid supplementation has been essential to produce meat, milk, fish, and eggs in large quantities. Smaller amounts of protein-rich raw materials can be used in animal feed due to amino acids. This reduces the limited resources used and improves animal performance while lowering production costs. Awareness of additional

benefits, such as improved animal health and reduced environmental impact, is also growing. It has been reported that amino acid supplementation can reduce nitrogen excretion by up to 50% in animals without detrimental effects on performance [87].

6. Effect of animal feeds on the environment

The demand for livestock products is projected to grow massively in the next decades. By 2050, the global demand for animal products is projected to increase by 60 to 70%, and crop protein demand will increase by 100–120%. The developing world will have a big share in this increase [88, 89]. Feed-food competition is more likely to escalate, especially on maize and soybean, used for animal feeds production.

This projected demand for animal food and feed can have negative effects. Locally, these effects include land conversion, deforestation, air and water pollution, and land degradation. Approximately 20% of the global pasture and grazing land has been degenerated by livestock-related damage. The animal production industry contributes 8–18% of GHGs, which is a significant share considering their projected future growth [90].

According to Cheng et al. [91], livestock emissions account for 14.5% of total anthropogenic activities. The three main GHGs emissions are CH_4, carbon dioxide (CO_2), and nitrous oxide (N_2O), which, respectively, contribute 50, 26, and 24% of the total livestock emissions. CH_4, mostly from enteric fermentation and manure storage, has 28 times the global warming potential of CO_2. Nitrous oxide, from manure storage and fertilizers, has a global warming potential 265 times higher than CO_2 [92].

Regarding emission sources, CH_4 from enteric fermentation, manure management, and rice production for feed contributes to the largest share of the total emissions. Overall, CH_4 represents 54% of all animal husbandry emissions, while CO_2 and N_2O are smaller contributors at 31 and 15%, respectively (**Table 3**) [93].

Among the livestock species, cattle are the primary contributors to GHGs emissions, accounting for approximately 62% of total livestock emissions. Emissions from animal husbandry come from pigs 14%, chickens 9%, buffaloes 8%, and small ruminants 7%. Accordingly, meat production accounts for the largest share of emissions at 67%, dairy 30%, and eggs 3% (**Table 4**) [93].

Ruminants are the main producers of the greenhouse gas emissions. They produce methane and carbon dioxide through their ability to digest fibrous feed through bacteria in their rumen. In fact, livestock production contributes more greenhouse

Source	Emission level (%)	Source	Emission level (%)
Enteric fermentation, CH_4	46	Embedded on-farm energy, CO_2	0.5
Manure, CH_4	7.8	LUC: soybean and palm, CO_2	1.6
Feed: rice, CH_4	0.3	LUC: pasture expansion, CO_2	9.3
Manure, N_2O	5.0	Post-farm, CO_2	5.4
Feed, N_2O	9.8	Feed, CO_2	12
Direct on-farm energy, CO_2	2.5		

LUC: Land-use change.

Table 3.
Total emissions by sources calculated with global livestock environmental assessment model.

Species	Emission level (%)	Products	Emission level (%)
Cattle	62%	Meat	67%
Chicken	9%	Milk	30%
Pig	14%	Egg	3
Goat	4%		
Buffalo	8%		
Sheep	3%		

**for the year 2015.*

Table 4.
Emission sources by species and products.*

gas emissions than all forms of transport combined, which is responsible for 13% of global emissions. Besides, ruminants need a lot of feed and water, which increases pressure on earth's natural resources. They also accelerate deforestation, which has resulted in the fading possibility of using carbon sequestration in fighting climatic change [94].

Livestock production is one of the most serious threats to rainforests around the world. The world's diverse ecosystems are being destroyed, mainly to make way for pasture and arable land for the production of animal feed. Pasture creation alone is responsible for around 80% of Amazon rainforest deforestation. Crop cultivation, mainly soya, is also linked with rainforest destruction. In 2020, 42,000 km^2 of tropical rainforest was lost. Unfortunately, mankind has destroyed about 34% of the global tropical rainforests and caused the destruction of another 30%. Most of this destruction has taken place in and around the Amazon rainforest, more than half of it. Rainforests are home to around 50% of the world's plant and animal species. Unfortunately, when their habitats are destroyed, these species are threatened with extinction [95].

Continued efforts to meet global animal protein demand through intensive livestock farming will encourage more water pollution, deplete fresh water needed for human consumption, and increase climatic change. Simultaneously, climate change will exhibit higher temperatures, increase precipitation variations, and more frequent extremes, which negatively affect livestock production. The climate change impacts on livestock farming are broadly classified as direct and indirect: Direct effects relate to the effects of climate and CO_2 on thermal regulation, metabolism, immunity function of animal, and production quantity. Increased temperature (heat stress) results in lower feed consumption, reduced animal products, etc., meat and milk production, decreased reproductive performance, negative effects on immune functions, and increased mortality. Indirect effects arise from the influence of climate on feedstuffs production, water supply, pests, and pathogens. Increased CO_2 levels, rising temperatures and changing precipitation patterns, more frequent extreme climate events lead to changes in feedstuffs yield, changes in pasture composition and forage production, changes in forage quality, decreasing water availability and increasing water use, greater seasonal variation in resource availability, increased disease, pest, and parasite stress (**Table 5**) [91, 96].

Several feeding strategies have been developed in sustainable animal production to reduce the environmental impact of gas emissions, manure management, and feed production. The aim of these strategies is to improve production performance,

Impact type	Observed impact	More influential factors
Direct impact	Reduced feed intake	Increased temperature (heat stress)
	Decline in milk and meat production	
	Decreased reproductive performance	
	Negatively affected immune functions	
	Increased mortality	
Indirect impact	Change in feedstuff crop yield	Elevated CO_2 level
	Changes in pasture composition and forage production	
	Changes in forage quality	Increased temperature and elevated CO_2 level
	Shrinking water availability and increasing water use	Increased temperature
	Larger seasonal variation in resource availability	More frequent extreme climate events
	Increased disease, pest, and parasite stress	Increased temperature and changes in precipitation pattern

Table 5.
Climate change impacts on livestock production.

animal health and welfare, and to reduce the harmful effects of feed and/or raw material production and manure management. The environmental impact of animal production can be reduced through the regulation of the digestive system, the use of technological processes and precision feeding, and the use of feed additives to increase nutrient digestibility. To reduce the environmental impact of feed production, life-cycle assessment of feed production, the use of alternative protein sources, and the application of hydroponic farming models enable environmentally friendly and sustainable production.

7. Sustainability of the animal feed and feed additive industries

The sustainability of livestock farming and animal products consumption is regarded as the heart of the key challenges of modern food production. The feed sector has an important role to play in improving the sustainability of animal production and animal welfare, the reduction of greenhouse gas emissions and nutrient waste, the prevention of antimicrobial resistance, and the protection of forests and the environment [97]. Some of the promising solutions include; the use of novel feed resources that are not usable by humans, such as agro-industrial by-products, seaweeds, insects, leaf meals, single-cell proteins, protein isolates and hydrolysates, spineless cactuses, co-products of ethanol and biodiesel industry, and food wastes. Using grassland efficiently also offers possibilities for increasing carbon sequestration, land reclamation, and livestock productivity. There are also opportunities in decreasing feed wastages through increased harvesting crop residues efficiently and converting them into complete feeds such as densified feed blocks or pellets. In addition, it is also important that the animals are fed in accordance with their nutritional requirements [89].

8. Sustainable feed ingredient sources

Livestock fodder and feed production occupies most of the available agricultural lands globally covering approximately two times more land than food crop production. Increase in soybean cultivations has been the main driver for land-use change (LUC). Increasing soybean production for animal feed is associated with increased land degradation in the Brazilian tropical rainforest, one of the world's most important biodiversity hotspots [98, 99].

Although soybean is still considered one of the most balanced protein sources for optimal animal growth and production. Various researchers have shown that alternative proteins from local, soilless, and circular sources can sufficiently replace conventional feed ingredients from a nutritional point of view. Furthermore, the use of such alternative protein sources can also provide solutions to the critical sustainability issues of conventional feed production [99, 100].

Pexas et al. [99] highlighted that genetically modified/engineered crops (mainly soya, potato, and maize), due to their resistances to pests, weeds, drought, and disease, can provide abundant and healthy protein year-round without the excessive use of synthetic and chemical inputs and water resources. Reduced use of fertilizers, pesticides, and insecticides can help improve the ecological quality of water and prevent loss of biodiversity by preventing the leaching of such chemicals into freshwater and coastal environments. In this case, however, the introduction of transgenic lines into weeds carries the potential for adverse effects and the risk of the emergence of herbicide-resistant superweeds. This should be considered, particularly in the context of water safety, as it could lead to an overall increase in herbicide use.

There are many opportunities for agriculture and animal production to become more resource efficient through the application of 'circular economy' principles. Animals use relatively high levels of inputs, much of which is not converted into edible products but results in wasteful and environmentally damaging outputs. Opportunities can be identified at all stages, from primary production using precision farming techniques to the recycling and use of agricultural waste, by looking at the whole agri-food system from a circular economy perspective [101].

Dairy cattle are an example that can be made sustainable by changing their feeding methods. Dairy cattle can use pasture plants, a resource not available to humans as food. However, many are fed concentrates that could be used by humans, resulting in poor welfare due to lameness, mastitis, or reproductive disorders. Some high producing cows are fed 40% concentrates, with up to 96% of their dietary protein available for human consumption. This system results in a net loss of nutrients for humans. However, if the cows were fed a diet of 70% or more forage and 30% or less concentrates, the system would be a net nutrient gain for humans [102].

Semi-intensive silvopastoral dairy production systems are more productive than fertilized pasture systems, use less water, manage the soil with consideration for worms and water retention, encourage encourage predators of harmful animals, minimize greenhouse gas emissions, improve job satisfaction for farmers, reduce animal injury and stress, and maximize welfare. Semi-intensive silvopastoral systems for beef production use one-fifth of the land and between one-quarter and one-sixth of the conserved water used by fertilized pasture or feedlot systems [102].

9. Nutritional solutions

Recent advancements in nutritional science have revolutionized the field of animal nutrition, offering new insights into personalized feeding strategies and the optimization of nutrient utilization for improved health and performance. By understanding the unique genetic make-up of individual animals, nutritionists can tailor dietary interventions to optimize nutrient metabolism, mitigate genetic predispositions to certain diseases, and enhance overall animal well-being. Recent research has focused on enhancing the bioavailability of key nutrients through innovative formulation techniques and ingredient selection [100].

Improvements in feeding good quality forages have shown positive feedback in reducing CH_4 emission. Quality forage is achieved by better management of grasses in pastures and by growing better forage in the 'cut and carry' systems that predominate in much of Asia and much of Africa. Other improvements that both increase production and reduce CH_4 emission intensity include the use of mineral supplements and other additives in livestock rations. Feed additives fall into two broad categories: those that alter the rumen environment in a way that inhibits the growth of CH_4-producing archaea, and those that directly interfere with some step in the CH_4 production process [103].

Feed formulation will continue to play an important role towards sustainable livestock industry. Formulation ensures that animals receive optimal nutrition, contributing to economic viability and environmental sustainability. Formulation that includes feed additives, such as probiotics, prebiotics, enzymes, etc., are presented as a top solution pertinent to the feed industry [23, 104]. The incorporation of feed additives in feeds has led to increased usability of non-conventional feeds, improved nutrient utilization and gut health, which resulted in reduced feed costs, increased animal farming business profitability, and reduced environmental pollution.

Precision feeding is a practice that involves customized diets tailored to individual nutritional requirements. By reducing feed waste and minimizing nutrient excretion, precision feeding is a powerful solution for reducing the environmental footprint of livestock production. This includes a significant reduction in greenhouse gas emissions and the prevention of water pollution. The future trajectory of precision feeding is intrinsically tied to the resolution of pressing challenges, including the need for real-time monitoring, the development of cost-effective large-scale implementation, and the comprehensive elucidation of long-term effects on animal health and welfare. From optimizing resource efficiency and reducing environmental impact to formulating personalized nutritional strategies, the resulting overview offers promising prospects [105]. The use of innovative technologies in animal production will contribute to animal health and welfare. It will also make a significant contribution to the economic sustainability of animal production by reducing costs in the long term through more efficient and higher quality animal products.

10. Application of artificial intelligence and digital technology in livestock farming

Technological advances, such as smart technologies, the internet of things, cloud computing, etc., can help livestock farming adapt to the future. Some basic problems, such as yield loss, excessive use of water, feed, additives, and medicines, can be prevented through smart livestock applications, such as sensor technologies, data processing, cloud systems, management, and prediction.

Digital tools are transforming feed management and animal nutrition. The internet of things, sensors, and artificial intelligence enable precise tracking of feed intake, animal growth, and health parameters. Big data analysis optimizes feed strategies, improves productivity, and forecasts disease. Blockchain technology improves traceability and transparency in the feed supply chain and addresses food safety and sourcing concerns.

The use of advanced digital technologies on farms helps to optimize the economic contribution per animal, reduce repetitive tasks, and activate more effective solutions. This trend will support further research on topics such as the use of new biometric sensors, big data, and blockchain technology for the mutual benefit of producers, consumers, and farm animals. High-tech will focus on interoperability, creating a digital ecosystem for farms. Sensors, drones, and software will share data, providing insights and improving productivity and sustainability. As these technologies develop, accessibility will be crucial. It is important to ensure that all farmers can benefit from these advances. Education, training, and resources must be made available [106].

11. Multistakeholder partnership to address complexity and diversity

Global demand for animal proteins, such as meat, eggs, dairy, and fish, is increasing due to population growth, urbanization, and rising incomes. At the same time, the issue of making global food production and consumption more sustainable is becoming increasingly urgent, particularly in light of limited resources and the need to reduce environmental pressures. The contribution of animal feed to the carbon footprint of animal products is significant due to the cultivation, transport, and processing of ingredients, as well as the impact of livestock farming. However, significant improvements in the sustainability of animal products are possible.

There is a need to make livestock production more environmentally friendly with appropriate, practical, and economic strategies, without compromising performance and health. This is a broad and topical issue, and in addition to improving animal performance parameters, it is important to consider environmental impacts and implement appropriate strategies. Socio-economic sustainable performance means ensuring a safe and efficient livestock production system with good opportunities for farmers in local, national, international, or global food supply chains.

Given the diversity of the livestock sector, its potential to contribute to development goals is significant. Solutions to meet growing demand vary according to production systems, stakeholders, and economic conditions. Implementation is the responsibility of governments, the private/public sector, civil society organizations, research centres, academia, and all stakeholders. The global agenda for sustainable livestock requires an inclusive partnership at all levels, based on a shared vision, agreed goals, and principles that put people, animal welfare, and the environment we live in at the centre, while recognizing different pathways to improved sustainability. This partnership provides an integrated approach to mobilizing and sharing knowledge, developing cutting-edge tools, and strengthening policy [107].

12. Conclusion

The demand for livestock products is nearly unstoppable due to the steady and projected growth of world's population, urbanization, and increasing incomes by

2050. The livestock sector can only meet future demand by increasing the number of animals and improving productivity. Increasing animal numbers will certainly increase the demand for animal feed. Some of the strategies to meet the feed demand will involve utilization of non-conventional feedstuffs (insects, seaweeds, genetically modified crops, etc.), efficient use of the available feed through advanced feed formulations and the application of artificial intelligence, and improving the value of available feed resources using feed additives. Combining these strategies will result into profitable and sustainable livestock farming with less effect on the environment and considerably decreased GHGs emissions, which lead to global warming and climate change.

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Chapter 3

Use of Food Waste in Animal Nutrition

Sibel Soycan Önenç

Abstract

Meat, milk and eggs derived from animals play an important role in ensuring an adequate and balanced diet for human beings. Between 50 and 70% of their production costs are feed costs. The profitability of the business is greatly affected by increases or decreases in feed costs. It is important that the feed used in livestock farms is high quality and inexpensive. Animal nutritionists and the feed industry, through their research into the evaluation, processing and use of new feeds, have turned to cheap and readily available alternative sources of crude matter not previously used as feeds to reduce feed costs. Alternative feed sources play an important role in reducing feed costs by ensuring that feeds within the same nutrient group are preferred over each other. In today's world of recycling, many studies have been carried out on the use of expired food, food that poses a hygiene risk to humans but not to animals, or food industry waste in animal nutrition. In this section, the studies will be reviewed and the results will be evaluated.

Keywords: food waste, alternative feed, animal nutrition, recycle, sustainability

1. Introduction

In many parts of the world, the use of food waste and food production residues (leftover food) as animal feed has been a traditional practice for many years [1]. The feeding of animals with food materials that are not suitable for human consumption is a source of valuable food products such as meat, milk and eggs, and is a means of recycling [1–4]. In modern production systems, this method is used less frequently [1]. These include intensive animal feeding programmes that ensure maximum efficiency through precise feeding with the use of feed grains such as maize and soya beans [4]. Food waste from different sources causes variability in nutrient content. In modern production systems, this limits the use of food waste. However, a very important and overlooked aspect of food waste is its impact on society and sustainability. Today, there is a growing interest in re-applying traditional methods to solve new problems, as climate and sustainability challenges increase [1–15]. Any reduction in the quantity or quality of food throughout the food supply chain [16], in other words, losses that occur during the production, post-harvest and processing stages [6], is referred to as food loss [6, 16]. However, food waste is defined as: "any change in the availability, edibility, integrity or quality of food that prevents it from being consumed by humans". In other words, it is defined as healthy edible material intended for human consumption that is produced

at any point in the food supply chain and that is thrown away, lost, spoiled or eaten by pests instead of being consumed [6, 17]. There is no formal distinction between the two in the literature. Therefore, 'food waste' can be replaced by 'food loss' [7]. Food waste is defined as the disposal of food and beverages that were once edible before being thrown away, according to the Waste and Resources Action Programme [18]. In addition, the definition of food waste was emphasised: "It consists of raw or cooked food and includes food lost before, during or after food preparation in households, as well as food discarded during production, distribution, retail and food service activities" [18].

Throughout the food supply chain, food waste can be prevented or unavoidable waste. Preventable waste is waste that could easily be converted into a useful product, but which ends up in a landfill. Unavoidable waste is the part of food that cannot be eaten by humans. It includes some fruit and vegetable peels, bones and eggshells. However, unavoidable waste can also be transformed into useful products. A frequently observed correlation is an inverse relationship between food insecurity and food waste. Food insecurity is defined as the difficulty in providing a sufficient supply of food for the human population [7]. It is evident that a number of factors contribute to food losses in the initial stages of the food supply chain. These include, but are not limited to, losses that occur during the harvesting process, such as edible crops that are left in the field or crops that are damaged during the harvesting process. Additionally, losses can also arise during the transportation and storage of food. During the later stages of the supply chain, there is a possibility of product loss occurring during processing, product evaluation, packaging and marketing. The sources of final stage food waste are as follows: households, food service enterprises (e.g. restaurants, the hospitality sector and cafes) and institutions (e.g. educational institutions, prisons and hospitals) [6].

The issue of food waste is a pervasive problem, with ramifications for the environment, society and the economy [3]. Indeed, the issue under discussion is closely related to that of food security [4]. While 13.2% of global food production is wasted before reaching retail, 17% occurs at retail and consumption [19]. The issue of food waste represents a significant global problem that is currently being faced by humanity. It is evident that the existing food systems are inadequate, with estimates suggesting that between one-third and one-half of all food produced is wasted before reaching consumers [5]. It has been determined that one-third of the total food production of the world each year is either lost or wasted. This results in a total of 1.3 billion tons of consumable food being discarded each year [1, 4–8].

According to the Food Waste Index report (FWIR), the annual global production of edible food that is subsequently wasted is estimated to be 931 million tons, with a financial cost to society of approximately $1 trillion per year [3, 19]. A study of food waste generation across different levels in various countries has identified the United States, China, the European Union (EU), Saudi Arabia and Australia as the leading countries [5]. A substantial quantity of food waste, comprising both edible and inedible components, is produced within the EU on an annual basis. This waste is estimated to total 88 million tonnes [6]. In the EU, the following proportions of lost or wasted food are recorded: 12% from food services, 53% from households, 5% from wholesale and retail and 30% from manufacturing and processing [6]. In some social and cultural contexts, the preparation of substantial quantities of food is a requisite element for the purpose of symbolising such values as charity, wealth and social status. This leads to significant food waste. The FWIR, published in 2021, indicates that India is the world's seventh-largest generator of food waste, with an annual domestic production of 50 kg of food per person [18].

It is estimated that approximately 40% of food waste in industrialised countries originates at the retail and consumer levels [7]. In the context of developing countries, a greater proportion of food is unfortunately lost during the initial and medial phases of the food supply chain when compared with food waste in the subsequent phases, specifically in the retail sector and during final consumption. This shows that food losses occur mainly during production, processing and storage [6].

2. Classification of food waste

In recent years, many studies have been carried out on the recycling of food waste through animal feed. The food waste used in the studies varies widely in type, source and form. Depending on the species and physiological period, the composition of the ration (energy, protein, amino acids, etc.) and therefore the costs vary. Food waste should be grouped because it is heterogeneous [1]. The grouping should be conducted in accordance with the following parameters: firstly, the potential suitability for animal feeding must be considered; secondly, the available quantities must be taken into account; finally, the source of production must be identified [4]. The classification of waste as being either of a plant or animal origin is dependent upon its nature and provenance [8]. In a similar fashion, depending on the mode of cooking, the food waste may be classified as being raw or uncooked, or as having been cooked or semi-cooked. Throughout the production process, food is transported from producer to consumer in a variety of ways, and waste is generated at each of these levels [2]. Agriculture represents the initial link in the food chain, with growers thus being regarded as primary producers. As previously outlined, losses can also occur during transport from the field to the warehouse, from the warehouse to the grain cleaning and sorting facilities, or to distribution networks. Furthermore, a loss of grain is also possible during storage, milling, processing and marketing. It is evident that the most significant losses, which arise from an ethical and moral standpoint, are those that transpire prior to or in the aftermath of food preparation in both domestic and culinary settings. These losses are predominantly attributable to negligence and a paucity of meticulous planning [9]. In the context of the food industry, consumers are considered to be at the pinnacle of the supply chain. In consideration of the aforementioned factors, the classification of food waste can be determined as follows [2]:

1. Agricultural food waste: Those originating from farmers.

2. Industrial food waste: Those produced by wholesalers.

3. Market food waste: This category comprises fresh and uncooked food items that are produced by secondary distributors.

4. Hotel and restaurant food waste: Cooked products produced additionally by secondary distributors.

5. Domestic food waste generated by consumers (clients).

They are classified as solid, semi-solid and liquid food waste according to their physical state [2]. This classification is particularly important for waste disposal. Manufactured food is sometimes referred to as 'stale food' if it has been removed from

the human food supply chain because it does not meet certain product specifications or because of incorrect labelling, packaging, etc. Examples of stale foods include sugary confectionery, salty snacks and excess baked goods [1].

Food waste occurs at every stage of the food system, from farm to table. In developed countries, consumer-facing businesses (supermarkets, grocery stores, distribution centres, restaurants, institutional food services) and households account for the largest waste stream at the end of the food chain. The second is food waste at the consumption stage in consumer-facing businesses. In many developed economies, a large proportion of food waste is sent to landfills at the consumption stage. To reduce the burden on landfills worldwide, alternative options are being promoted. These include composting, anaerobic digestion, incineration and livestock feeding. In particular, sustainable food security issues are not directly addressed by any option other than animal feed [4].

3. The environmental impact of food waste

Food waste is a problem with significant environmental impacts, such as the production of greenhouse gases in agriculture [1], the reduction of biodiversity [3], ecological degradation, excessive contamination of soil and water with nutrients, herbicides and pesticides [2, 20]. Inequalities in food production, distribution and consumption around the world have led to excessive food waste [2, 7]. The movement of people from rural areas to urban settlements and the continued production of waste are further complicating these factors and exacerbating the problems [2, 7]. Therefore, the management of food loss and waste is of great importance [2]. Scientists estimate that by 2050, ~68% of the world's population will live in cities, while ~30% will remain in rural areas. It is also thought that people living in rural areas may not be able to provide themselves and urban dwellers with large amounts of fruit, vegetables and meat products [2, 7]. It is estimated that 22% of food waste, generated at various points in the food supply chain, is disposed of in landfills [7]. It is an established fact that livestock producers have historically fed their animals food waste instead of grain or protein sources [2].

The issue of food waste is of particular concern when considered in relation to significant environmental degradation and the erosion of fertile soils. This is due to the complex nature of food waste and its high moisture content. Moreover, the issue of pollution in landfills is exacerbated by the presence of food waste, the occurrence of leachate formation and the presence of malodorous and pest-infested conditions [5]. Furthermore, the issue under discussion has been demonstrated to engender water scarcity (leachate), agricultural land erosion and biodiversity [3]. In the course of food production, distribution and waste disposal, the release of substantial quantities of gases such as methane and carbon dioxide into the atmosphere is a consequence [5, 13]. Moreover, the degradation of organic matter in an anaerobic environment leads to the production of methane gas (CH_4), which has a negative environmental impact that is 25–37 times greater than that of carbon dioxide (CO_2) [3, 5, 13]. Methane has been identified as a significant greenhouse gas, with a considerably higher global warming potential than carbon dioxide [5]. Annually, the global production of food that is subsequently discarded amounts to a quantity of 1.3 billion tons. This process gives rise to the emission of 3.3 billion tons of carbon dioxide [3, 5]. In 2017, the worldwide emissions of food loss and waste from supply chains and waste management systems amounted to 9.3 Gt CO_2 equivalent. This is responsible for approximately 50% of the total annual greenhouse gas emissions from the global

food system [13]. According to the Food and Agriculture Organisation (FAO), the carbon footprint of global food waste is estimated to account for approximately 8% of all greenhouse gas emissions caused by human activity. For every kilogramme of food produced, 4.5 kilogrammes of CO_2 are released into the atmosphere. The magnitude of food losses remains consistent across both industrialised and developing countries, with a reported 670 million tons in the former and 630 million tons in the latter. The distinction lies in the fact that within low-income countries, the most significant losses transpire at the inception of the production and supply chain. Conversely, in middle- and high-income countries, edible food is frequently discarded even when it remains fit for consumption [14].

In accordance with European legislation, food waste is permitted to be utilised as a constituent of animal feed for fur-bearing animals and companion animals, subsequent to the rigorous management procedure that necessitates sterilisation [4, 6]. The process of sterilisation has been shown to engender a considerable increase in the cost and environmental impact, owing to its substantial energy requirements. The animal feed industry's recognition that foods deemed unfit for human consumption do not constitute waste, but rather represent alternative feed sources, has the potential to significantly reduce the volume of waste disposed of in landfills on an annual basis. At the same time, it reduces feed costs and reduces environmental damage, thus reducing the environmental footprint of the feed production process [10].

The processing of food waste is a critical step in the production of safe feed [1]. Depending on the particular type of food waste in question and the conditions it is in, a range of methods are employed for the purpose of recycling and reuse [5]. These methods include composting, the production of renewable bioenergy, animal feed production, food recovery, redistribution and industrial applications. The implementation of recycling methodologies has been demonstrated to assist in the mitigation of environmental impacts, the conservation of resources and the reduction of the social and economic ramifications associated with food waste [3, 5, 7]. It is imperative to minimise food waste in order to optimise the utilisation of resources, reduce environmental impacts and promote sustainable agricultural practices [5]. The utilisation of food waste as a substitute for conventional feed ingredients, such as corn and soybeans, has the potential to engender a reduction in greenhouse gas emissions, nutrient losses and other forms of pollution. This approach may also result in a reduction in the consumption of land, water, fuel and fertiliser, thereby engendering a cascading effect. Moreover, it has been demonstrated that food waste that is disposed of in landfills in a number of developed countries contributes to methane emissions in a disproportionate manner [1]. In order to address the environmental issues posed by food waste, there is a necessity for the development of alternative methods that can be utilised for the purpose of recycling food waste and transforming it into higher-value products. This will serve to minimise the impact of food waste on the environment, thereby promoting the long-term sustainability of the food production system [2]. In order to ensure the sustainable use of resources throughout the food system, efforts to address food waste should focus on the following three areas: the prevention of food waste, the efficient management of supply chains and the raising of consumer awareness [5].

4. Food waste and the circular economy

Animal feed occupies a pivotal position within the food chain, exerting a significant influence on the composition and quality of animal products (e.g., meat,

milk and eggs) that are subsequently consumed by humans [7]. The utilisation of non-human foodstuffs as animal fodder has been explicitly incorporated into both the EU Commission Report and the updated EU Bioeconomy Strategy, on the condition that the prevailing regulations and legal stipulations for the safeguarding of human health are adhered to [10, 11]. The bioeconomy and the circular economy are two such concepts that are at the forefront of this paradigm shift. In accordance with the provisions stipulated within the Circular Economy Action Plan, the term "circular economy" is defined as follows: the long-term preservation of product value, materials and resources in the economy through the reduction of waste production. It is vital to acknowledge the significance of food waste as an integral component of the circular economy. This issue should be given careful consideration at various points along the value chain [2]. The concept of a circular economy has garnered considerable attention in recent years as a strategy to address the sustainability issues inherent in the linear system. Such issues include material scarcity, climate change, depletion of natural resources and waste generation. The circular economy can be defined as an economic model aimed at eliminating waste by recycling materials within processing systems. The principle underpinning this model is the notion that "waste equals food". This principle is predicated on the notion that the concept of recycling is to be extended beyond the mere recycling of materials to encompass the concept of upcycling. The latter is defined as any process that is capable of transforming waste into higher-value products by using it as the input for the production of other products. In essence, the circular economy is designed to facilitate the transformation of "one person's waste into another person's resource", a concept that has the potential to encourage sustainable consumption habits [18].

While the main effort to reduce food waste should be focused on prevention, returning it to the food supply chain is a prerequisite for implementing the principles of the circular economy, which sees waste as a resource [6]. This circular bioeconomy model minimises waste generation through the reuse, renewal and recycling of materials and products for as long as possible [12]. The feeding of food waste to animals, a food waste recovery measure based on the practical application of the EU food waste hierarchy [11], has been in practice worldwide for many years [7], but its disadvantage is the risk of diseases such as foot-and-mouth disease and swine plague in animals [10]. In the quest for a circular agri-food system for a more sustainable future, the recovery and reuse of large amounts of food waste is essential. In comparison to other recycling options, the upcycling of food waste through animal feed is a strategy that creates the greatest value by simultaneously addressing food security, climate change, resource constraints, biodiversity loss and other sustainability issues [1]. Food that is discarded and digested ends up as organic waste, in energy recovery or in a landfill [2]. The issue of food waste is twofold, being both a resource and a sustainability issue [1, 4]. A substantial proportion of this loss is attributable to fruits and vegetables. It has been estimated that this amount would be sufficient to feed more than one billion people [1, 4, 5]. In addition to the depreciation of resources such as labour, water, energy and land that are utilised for food production, this process also engenders financial losses for retailers and consumers [2]. As stated in Target 12.3 of the United Nations' Sustainable Development Goals, the objective is to reduce food losses at the consumer and retail levels throughout the entire food supply by half by the year 2030 [3]. It is evident that food production processes consume substantial resources, including land, water, energy, fertiliser and other inputs. These processes have a detrimental effect on the environment, giving rise to a number of problems, including biodiversity and habitat loss, soil and water degradation and greenhouse gas emissions [4].

5. Use of food waste in animal feed production

Despite the implementation of various initiatives, global food waste continues to be a pervasive problem, with no discernible decrease in comparison with a decade ago [1]. It can thus be posited that food waste can be considered as a reflection of human behaviour as opposed to a reflection of the quality of the food itself [7]. The generation of food waste is an inherent aspect of the diverse stages of the food supply chain. These stages encompass production, harvesting, processing, handling, distribution and retail [5]. The processing of food waste is imperative for its incorporation into animal feed, owing to its presence of undesirable characteristics, such as variable nutrient content [6]. The processing technologies available in the present day have the capacity to convert food waste into animal feed products that are both safe and of a higher quality than previously available, as well as products that contain additional nutrients [4]. The processing of food waste encompasses a variety of processes, including cooking, extrusion, pelleting, dehydration, ensiling and probiotic processes. It is imperative to treat food waste properly in order to minimise the risk of disease transmission between animals and between animals and humans. This can be achieved by ensuring sufficient microbial reduction in order to guarantee safety. In countries where the provision of these products for consumption by animals is permitted, a specific procedure must be undertaken prior to their provision. In the United States, the requirement for the treatment of food waste is that it should be subjected to a temperature of 100°C for a duration of 30 minutes. In Japan, the term "ecofeed" is used to denote processed food waste designated for animal feeding. The production of Ecofeed entails the cooking of raw materials that may contain uncooked meat. These materials are required to undergo a heating process at temperatures of 70°C for a duration of 30 minutes, or alternatively at 80°C for 3 minutes [6]. The recycling of food waste for the purpose of animal feeding (ReFeed) has emerged as a viable solution that holds the potential to address multiple issues concurrently, including waste management (i.e., reduction of landfill), food safety concerns and challenges related to resources and the environment. This process will also result in a reduction of feed grains, resources and environmental burdens linked with feed grain production. It is possible for farmers to increase their income by utilising food waste in order to reduce the cost of animal feed [4]. Nevertheless, there are certain disadvantages associated with the utilisation of food waste as animal feed. These include a lack of safety, an unpredictable nutritional profile and expensive production costs. Due to the high water content, it has been determined that food waste is susceptible to deterioration during collection, transportation and storage [2]. Nevertheless, legislative measures have been implemented in the USA and Japan to address this issue, establishing specific regulations pertaining to the collection, handling, storage and transportation of food waste [6].

In order to reduce the burden on landfills worldwide, a range of alternative options are being promoted, including composting, anaerobic fermentation, incineration and the use of waste materials as a feed source for livestock [4]. It is recommended that the origin of food waste intended for use in animal feeding be strictly regulated. In addition, during processing, food waste should be supplemented with other feedstuffs, thus creating a balanced diet [6]. Among these processes, extrusion, pelleting and dehydration provide a longer shelf life for the final food waste product compared to cooking and ensiling. Additionally, the process of dehydration can be instrumental in facilitating the integration of the resultant food waste products into the existing feeding programmes of swine [6]. As reported in a recent study, the concentrations of

dioxin, organic chloride, agricultural chemicals and heavy metals in chicken meat fed on dried food waste were found to be in accordance with regulations stipulated by the Food and Drug Administration (FDA) [15]. The processes of drying and installation of food waste (i.e., fermentation with lactic acid bacteria) are utilised to increase the shelf life of ecofeed. A range of technologies are employed to reduce the moisture content, nutrient variability and microbial load of food waste and to inactivate the presence of anti-nutritional factors. The processing of food waste prior to its utilisation in animal feeding is of paramount importance, as it facilitates the incorporation of the waste into the animal's diet [6]. It is evident that the utilisation of food waste as an alternative feed source will have a substantial impact on the resolution of issues afflicting the livestock industry. This industry is encountering instability due to suboptimal feed production and considerable costs [2].

6. Composition of food waste

In the context of wholesale, food is stored and sold in large quantities. The phenomenon of wholesale losses can be attributed to a number of factors, including the short shelf life of products, low demand, incorrect labelling and failures in the cold chain. Analogous issues have been identified in the retail sector, where financial losses are attributable to the following [7]:

- Packaging that has deteriorated
- Packaging that has been damaged
- Packaging that has been tampered with
- Packaging that has reached, or is nearing, its expiry date

Firstly, food waste can be a significant source of protein in the nutrition of animals. However, it should be noted that this relationship is not consistent across all species. A significant number of agricultural by-products, including milling residues and oilseed meals, are commonly utilised as animal feed. It is important to note that these by-products are generally not considered to be part of FLW (food loss and waste). As a result, they will not be discussed in this chapter [1]. As these products are not of animal origin, they are not subject to restrictions on their use as livestock feed. This classification encompasses items such as bread, biscuits, breakfast cereals, chips and candy [10]. These foods have a high nutritional value as a source of fat, sugar and carbohydrates. Consequently, the issue of how to dispose of food waste has been elevated to a position of increasing priority on the agendas of governments worldwide [10]. In this section, the food waste under discussion will be examined in terms of its application in animal nutrition.

The scarcity of feed resources in terms of both quantity and quality, coupled with the exorbitant cost of existing feedstuffs, has prompted feed producers and animal breeders to explore alternative feed sources. In animal nutrition, the use of many industrial wastes as alternative feed sources has been investigated. The expiration of foodstuffs utilised for human nutrition, consequent to the disturbances that transpire during the manufacturing process (e.g., spillage and damage to packaging) and the complications that ensue during transportation and storage, results in substantial

amounts of food waste. Many of these, including pasta, biscuits, cakes, waffle crumbs, instant soups and puddings, are used to feed animals on farms [21].

The results of a study carried out on dry food waste are shown in **Table 1** [21]. The food material in this study consisted of human food such as pasta, pudding, waffle meal, ice cream and bran mix, vegetable and yoghurt soups that had reached expiry date. Problems with storage increase as the amount of water in food waste increases. Korkmaz and Soycan Önenç [21] reported that high dry matter (DM) ingredients (98.69–87.15%) of products used in their research are not at a problem-causing level. It is also easier to incorporate into the ration due to its low water content. Analyses of the crude nutrient contents of pasta, pudding, vegetable soup, yoghurt soup, waffle meal and ice cream bran mix showed changes of CP 3.43–15.84%, EE 4.38–33.03% and CA 0.94–28.16% in DM. As these materials are being investigated for use as energy replacers in ruminant diets, it is suggested that they could be compared with the nutritional components of barley, wheat, oats, maize and wheat bran.

In one study, changes in DM of barley, wheat, oats, maize and wheat bran were reported to be 9.26–18.42% CP, 1.72–5.6% EE and 1.74–9.12% CA [22]. The CP contents in the DM of pudding and wafer meal were found to be lower, the EE contents of vegetable soup and wafer meal were found to be higher and the NFE contents were found to be similar to those of the materials in Abaş et al. [22]. In general, food waste contains a relatively high level of ether extract (EE). The EE of the wafer meal and vegetable soup are found to be 33.03% and 13.15%, respectively. Crude ash (CA) being determined to be high in vegetable soup and yoghurt soup can be explained with the salt and mineral content as calcium, magnesium etc. found in these soups. The salt content of food waste may be higher than that of conventional feed. Above-tolerance levels of salt in feed can be a cause of salt poisoning in pigs and poultry. However, if properly included in the ration, food waste can replace salt supplementation [6]. While soybean meal from traditional diets contains 0.27–0.47% Ca, 47.2% CP, maize has been reported to contain 0.01–0.03% Ca in DM [23]. In addition, pork can become soft and rancid more quickly due to the high salt content in pig feed [6]. Barley, wheat, corn and wheat bran, which are high in energy, are widely used in rations for ruminants. Korkmaz and Soycan Önenç [21], concluded that pasta, pudding, vegetable and yoghurt soups, waffle flour and ice cream bran mixture can be used as alternatives to the traditional feeds (barley, wheat, corn and wheat bran). The nutrient composition and metabolic energy content of food wastes used in various studies are shown in **Table 2**. The DM content of the jam liquid and particles is

Sample	DM*	CP*	EE*	CF*	NFE*	Starch*	Sugar*	CA*	ME**
Pasta	94.74	11.82	4.38	0.25	82.61	64.54	4.92	0.94	3457.6
Pudding	98.69	3.43	5.84	0.02	89.54	4.40	17.45	1.17	3480.1
Vegetable soup	95.29	9.27	13.15	0.57	61.85	54.86	7.16	15.16	3741.8
Yoghurt soup	93.94	15.84	7.79	0.35	47.86	29.04	24.20	28.16	3591.9
Wafer meal	87.15	4.75	33.03	0.06	60.20	39.59	32.13	1.96	4441.1
Ice cream bran mix	96.54	11.02	8.87	7.25	65.81	10.20	16.72	7.05	3329.3

*DM: Dry matter, CP: Crude protein, EE: Ether extract, CF: Crude fibre, NFE: Nitrogen-free extract, CA: Crude ash, ME: Metabolisable energy, Mix: Mixture, *: % in dry matter, **kcal/kg in dry matter.*

Table 1.
Nutrient composition and metabolisable energy values of samples.

Sample	DM	CP	EE	CF	NFE	WSC**	CA	ME	Ref.
Maize*	88.00	9.40	4.20	1.20	72.00	—	1.90	3450	[24]
Cornflakes waste*	94.70	6.74	3.80	2.74	81.28	—	0.14	3330	[24]
Wafer biscuit waste meal*	88.46	9.87	11.92	2.14	62.52	—	2.01	3805	[25]
Biscuit-wafer waste[a]	92.00	12.80	4.05	2.55	70.40	—	2.20	3300	[26]
Biscuit waste meal*	92.40	7.87	10.16	—	—	—	1.62	—	[27]
Pudding**	98.96	3.50	1.64	0.18	93.64	19.75	1.04	—	[28]
Wafer meal**	98.24	6.21	23.13	—	69.08	18.13	1.59		[29]
Whipped cream**	98.63	5.12	—	—	—	21.25	1.68	—	[30]
Jam liquid*	73.68	—	—	—	—	27.30	—	—	[31]
Jam particle*	75.34	—	—	—	—	—	9.19	—	[31]
Sour yoghurt*	12.99	5.48	—	—	—	9.03	0.97		[32]

*DM: Dry matter, CP: Crude protein, EE: Ether exract, CF: Crude fibre, NFE: Nitrogen-free extract, WSC: Water soluble carbohydrates, CA: Crude ash, ME: Metabolisable energy kcal/kg, Ref: Reference, [a]: Biscuit and wafer mixture was containing 60% biscuit with 40% wafer flour, * Nutrient composition: %, **: % in dry matter.*

Table 2.
Nutrient composition and metabolisable energy values of different food wastes.

relatively low compared to traditional feed maize. In addition, its high sugar content makes it difficult to transport and difficult to use. Sour yoghurt has a very low DM content and is very likely to spoil due to its high water content.

Therefore, it should be collected very quickly and delivered to the farms. It should be used with caution due to the growth of microorganisms in it. The presence of a low dry matter content renders these products suitable for incorporation into the total mixed ration. These food wastes, which contain low levels of DM, can also be used as silage additives. A comprehensive examination of studies on this subject has been undertaken within the silage section. The DM contents of other waste materials are higher than those of maize and can be readily incorporated into the ration. Food waste can be a good source of protein and fat, as long as there has been no deterioration in quality [23]. The CP contents of wafer biscuit waste meal and biscuit-wafer waste mixture were found to be higher than maize. The EE is present in high concentrations in wafer meal, wafer biscuit waste meal and biscuit waste meal. Due to the relatively high EE content of food waste and exposure to high cooking and heat treatment conditions during drying, lipid peroxidation may occur [23].

In another study [33], quinoa (white, black and red), chia (white and black), teff, mung bean and buckwheat were investigated as feeds (**Table 3**). However, they had expired due to tearing or damage to the packaging. Quinoa is known to have 125 different varieties of seeds. The commercial ones introduced in supermarkets in Turkey are white, black and red, although they have a colour scale that changes from green to grey. The research carried out has concluded that the highest levels of crude protein have been found in white, black and red quinoa, teff and buckwheat compared to many other crops, but lower than in legumes. Chia seeds contain 24% protein, 25–35% oil and 22% crude fibre (CF). They are also particularly rich in unsaturated fatty acids [34]. A study found that adding chia seeds to the ration did not have a negative effect on rumen fermentation, digestibility, microbial activity or rumen nitrogen (N) metabolism [35]. In comparison with barley, a traditional cereal, CP was

Sample	DM*	CA*	CP*	EE*	CF*	NFE*		NDF*	ADF*	ADL*	Hcellulose*	Cellulose*
						Starch	Rest					
WQ	93.09 ± 0.03^{b}	2.69 ± 0.01^{cd}	15.01 ± 0.02^{e}	7.68 ± 0.01^{d}	3.30 ± 0.04^{e}	58.85 ± 0.05^{c}	12.46 ± 0.07^{g}	22.29 ± 0.01^{g}	2.67 ± 0.08^{f}	1.78 ± 0.02^{g}	19.62 ± 0.08^{b}	0.90 ± 0.01^{h}
BQ	93.13 ± 0.02^{b}	2.76 ± 0.03^{c}	15.38 ± 0.06^{d}	7.13 ± 0.06^{e}	7.88 ± 0.05^{c}	48.66 ± 0.02^{e}	18.17 ± 0.05^{c}	29.12 ± 0.01^{d}	11.41 ± 0.07^{c}	3.87 ± 0.02^{c}	17.71 ± 0.07^{c}	7.55 ± 0.09^{c}
RQ	92.64 ± 0.06^{c}	2.55 ± 0.07^{d}	14.03 ± 0.08^{f}	7.97 ± 0.01^{c}	5.59 ± 0.02^{d}	51.27 ± 0.03^{d}	18.59 ± 0.10^{b}	23.21 ± 0.09^{f}	8.17 ± 0.02^{d}	3.25 ± 0.06^{d}	15.04 ± 0.08^{e}	4.92 ± 0.08^{e}
WC	96.13 ± 0.08^{a}	4.99 ± 0.06^{a}	19.90 ± 0.07^{c}	30.84 ± 0.02^{b}	20.95 ± 0.05^{a}	2.49 ± 0.01^{g}	20.85 ± 0.11^{a}	40.74 ± 0.11^{a}	29.76 ± 0.05^{a}	9.09 ± 0.05^{b}	10.98 ± 0.06^{g}	20.67 ± 0.09^{a}
BC	96.04 ± 0.05^{a}	5.11 ± 0.09^{a}	21.73 ± 0.02^{b}	35.75 ± 0.06^{a}	17.26 ± 0.17^{b}	2.37 ± 0.06^{h}	17.77 ± 0.29^{d}	32.47 ± 0.11^{b}	24.36 ± 0.05^{b}	11.30 ± 0.22^{a}	8.12 ± 0.09^{h}	13.05 ± 0.07^{b}
Teff	93.23 ± 0.06^{b}	2.26 ± 0.01^{e}	11.98 ± 0.01^{h}	2.46 ± 0.07^{h}	3.44 ± 0.05^{e}	65.99 ± 0.01^{a}	13.87 ± 0.13^{f}	20.22 ± 0.01^{h}	5.98 ± 0.03^{e}	3.09 ± 0.08^{e}	14.24 ± 0.04^{f}	2.89 ± 0.05^{f}
MB	92.71 ± 0.01^{c}	4.19 ± 0.08^{b}	25.20 ± 0.03^{a}	3.48 ± 0.09^{g}	5.58 ± 0.02^{d}	47.72 ± 0.02^{f}	13.83 ± 0.05^{f}	23.93 ± 0.05^{e}	8.11 ± 0.04^{d}	2.84 ± 0.08^{f}	15.82 ± 0.09^{d}	5.27 ± 0.04^{d}
BW	90.47 ± 0.05^{d}	2.10 ± 0.02^{f}	13.72 ± 0.03^{g}	5.25 ± 0.07^{f}	1.37 ± 0.02^{f}	62.24 ± 0.02^{b}	15.32 ± 0.09^{e}	31.29 ± 0.08^{c}	2.47 ± 0.04^{g}	1.30 ± 0.02^{h}	28.82 ± 0.12^{a}	1.17 ± 0.05^{g}
P	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

*WQ: White quinoa, BQ: Black quinoa, RQ: Red quinoa, WC: White chia, BC: Black chia, MB: Mung bean, BW: Buck wheat, DM: Dry matter, CA: Crude ash, CP: Crude protein, EE: Ether extract, CF: Crude fibre, NFE: Nitrogen-free extract, Rest: NFE-starch, NDF: Neutral detergent fibre, ADF: Acid detergent fibre, ADL: Acid detergent lignin, Hcellulose: Hemicellulose, *: Nutrient composition % in dry matter, ± SEM: Standart error of means,$^{a-h:}$ Means with different letters in the same column are statistically significant (P < 0.05).*

Table 3.
Nutrient composition and cell wall contents of samples.

Fatty acid*	WQ	BQ	RQ	WC	BC	Teff	MB	BW	P
Palmitic acid, C16:0	9.24 ± 0.02^{d}	9.22 ± 0.06^{d}	9.91 ± 0.07^{c}	7.23 ± 0.05^{e}	6.88 ± 0.06^{f}	13.44 ± 0.07^{b}	26.76 ± 0.06^{a}	13.61 ± 0.01^{b}	0.001
Stearic acid, C18:0	0.82 ± 0.01^{f}	0.74 ± 0.03^{fg}	0.60 ± 0.01^{g}	3.62 ± 0.01^{b}	2.72 ± 0.06^{d}	3.33 ± 0.06^{c}	4.38 ± 0.01^{a}	1.57 ± 0.05^{e}	0.001
Oleic acid, C18:1	26.97 ± 0.04^{d}	27.44 ± 0.03^{c}	25.44 ± 0.05^{e}	7.18 ± 0.01^{f}	5.68 ± 0.05^{g}	27.86 ± 0.06^{b}	1.82 ± 0.04^{h}	38.82 ± 0.07^{a}	0.001
Linoleic acid, C18:2	52.70 ± 0.01^{a}	51.96 ± 0.04^{b}	52.74 ± 0.03^{a}	21.23 ± 0.02^{f}	18.56 ± 0.03^{g}	47.05 ± 0.04^{c}	39.23 ± 0.07^{d}	36.80 ± 0.07^{e}	0.001
Linolenic acid, C 18:3	5.84 ± 0.03^{g}	6.55 ± 0.06^{f}	7.57 ± 0.06^{e}	60.75 ± 0.07^{b}	66.19 ± 0.02^{a}	8.31 ± 0.06^{e}	20.84 ± 0.04^{c}	5.34 ± 0.07^{h}	0.001
Arachidic acid, C 20:0	—	—	—	—		—	1.7148	1.3125	—
Arachidonic acid, C 20:4	2.3402	2.3024	2.2892	—		—	—	—	—
Behenic acid, C 22:0	0.7667	0.4948	—	—		—	3.5361	1.5131	—
Erucic acid, C22:1	1.3033	1.3714	1.3989	—		—	—	—	—
Lignoceric acid, C 24:0	—	—	—	—		—	1.7694	0.9379	—

*WQ: White quinoa, BQ: Black quinoa, RQ: Red quinoa, WC: White chia, BC: Black chia, MB: Mung bean, BW: Buck wheat, *: %, ± SEM: Standart error of means, $^{a-g}$ Means with different letters in the same line are statistically significant (P < 0.01).*

Table 4.
Fatty acid components of samples.

found to be higher than in barley, except for teff and buckwheat [22, 36]. However, nitrogen-free extract (NFE) was found to be high in teff but significantly low in white and black chia (**Table 3**). Baye [37] found that teff's CP, starch and CF contents were similar to maize, sorghum and wheat, traditional cereals used in animal nutrition. Food waste may also contain bioactive compounds. Bioactive compounds include long-chain polyunsaturated fatty acids (PUFAs), vitamins, carotenoids, peptides and polyphenols. The most important of these are eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA) and arachidonic acid [6]. The fatty acid compounds of quinoa, chia, teff, mung bean and buckwheat, which were used in the experiment, are given in **Table 4** [33]. The main fatty acids, linoleic, oleic, palmitic and linolenic, were found to be high in quinoa of three different colours. However, linolenic acid levels were high in both types of chia [33]. The addition of chia seeds to the ration can change the fatty acid composition of meat and milk due to their richness in omega-3 fatty acids [35]. Moreover, it was stated that chia oilcake is a good source of protein (19.0–23.0%) and fibre (33.9–39.9%), and it also contains antioxidants [34]. One study found that phospholipids and triglycerides were high in mung beans, and that the dominant fatty acids were linoleic and oleic [38]. In addition, high levels of linoleic acid have been reported in mung beans, teff and buckwheat [33].

7. Food waste utilisation in monogastric animals

It is an established fact that traditional swine and poultry diets rely on corn as an energy source and soybeans as a source of protein [6, 7, 39]. Non-ruminants are both pigs and poultry [7]. However, a large part of the world's population, especially in developing countries, relies on corn as its staple food [6]. The escalating global demand for grains has resulted in a persistent increase in prices. Therefore, there is a necessity for alternative feed sources to be utilised in place of traditional feed sources, with a view to reducing feed costs in livestock enterprises [39]. Feed costs are a significant component of meat production, impacting the financial viability of the enterprise [6]. In the EU, feed costs constitute 55–72% of pig production costs and 55–75% of poultry production costs. It is evident that a considerable proportion of by-products obtained from the human food industry have the potential to be utilised in pig and poultry diets [40]. The financial advantage of utilising food waste as a feed alternative, as compared to conventional feed options, has been demonstrated, leading to potential cost savings in production [6]. In addition to making a significant contribution to the fight against food insecurity, evidence suggests that it can also provide health benefits as it contains bioactive compounds [6]. It is recognised that the utilisation of food waste as chicken feed has the capacity to provide nutrients to animals and, indirectly, to humans [10]. As asserted by Stefanello et al. [39], it is necessary to evaluate the nutrients and energy usage of unconventional feeds. The processing of food waste is also a significant consideration, as the presence of mould in feed can compromise its nutritional value and pose a risk to animal health. Consequently, the process of drying or fermenting food waste has been identified as a method of preventing mould growth and should be given due consideration when integrating food waste as a constituent of poultry feed [6]. An experiment to evaluate discarded biscuits as an alternative to maize in pig diets was conducted by Manu [41]. They were fed ad libitum with isonitrogenous diets containing 0%, 10%, 20% and 30% levels of discarded biscuits, which replaced similar amounts of maize. He found that there were no significant differences in average daily feed intake, average total feed intake, average daily weight

gain, average total weight gain and feed conversion ratio (FCR) between the four diets. There was a linear decrease in feed costs with increasing discarded biscuits in the diet, and gain costs followed a similar trend. It was concluded that discarded biscuits could make up to 30% of the diet and replace about 60% of the maize in the diet of growing pigs without adversely affecting growth performance and carcass characteristics, thereby reducing competition for maize between humans and livestock. Poultry constitutes a significant component of animal husbandry. The demand for chickens is high in many regions worldwide due to their rapid growth rate and resilience. Chicken meat and eggs are one of the main sources of protein for many people in the world [7], who are heavily dependent on corn and soy as their main feed sources. It is thus imperative that the effects of alternative feed materials are subjected to rigorous scrutiny. Poultry diets are mainly based on maize and soya, and almost 60–70% of poultry requirements are met by cereals (energy source), mainly maize. Cereals are also needed for human consumption. This leads to increased competition between poultry and humans. Therefore, there is an urgent need to look for unconventional energy sources for poultry feed formulation to reduce feed costs [42]. The primary concern regarding the utilisation of food waste as a broiler feed is attributable to the high ligno-cellulose content thereof [7]. However, bakery flour is a constituent of products that are unsold or unsaleable, and are obtained from bakeries and food processing facilities.

This product is widely used in the feed industry [40] and can be readily incorporated into poultry compound feeds due to its very low ligno-cellulose content. Bakery waste is a by-product which can be used as an energy-rich feed for feeding animals. Its protein and amino acid content is similar to that of maize (10.8% CP, 0.27% lysine and 0.10% tryptophan). However, it has a higher fat content (11%). Similarly, a bakery meal is rich in starch. This is because wheat meal is the main ingredient in all bakery products. Since the starch is thermally processed (cooked), it is highly digestible and therefore has a high nutritional value [43].

In the nutrition of pigs and poultry, both the quantity and quality of dietary protein are important [6]. Indeed, a considerable number of by-products from the corn processing industry and other industries, including the bakery and grain industries, are frequently utilised in pig diets [44]. One of the earliest studies reported that when fed to pigs on pasture, oven-dried stale bread moistened with water was almost equivalent to corn. However, when not administered with a laxative feed, it caused constipation. It has been posited that oven-dried bakery wastes exhibit a composition analogous to grain, though they may contain reduced levels of fibre and elevated levels of oil [45]. Barman et al. [46] reported that up to 50% of maize can be replaced with bakery waste for the formulation of economic rations, with no effect on piglet growth, FCR and feed cost per kg gain. Bakery products are the result of a complex process involving the mixing, grinding and drying of a variety of ingredients, including wheat products, pasta, potato chip waste, cakes and breakfast cereals [44]. Bakery flour is a by-product of unsold or unsaleable products obtained from bakeries and food processing factories, and its main component is wheat flour. This ingredient can be successfully used as a part of grain replacement in broiler feeds as an energy source due to the presence of digestible starches and sugars within its carbohydrate composition [39, 45, 47]. In general, bakery meal contains around 2981 kcal/kg net energy, which compares very favourably with maize at 2672 kcal/kg net energy [48]. It can also reduce dependence on corn, which is the primary energy source [47]. It is estimated that 70–80% of corn production globally is utilised for the purpose of livestock feed [43]. It is estimated that demand for corn and soybeans will increase by 40% of the amount produced [7]. Damron et al. [45], determined that the addition of up

to 10% dried bakery waste to broiler diets did not significantly affect the live weight and feed conversion ratio of broilers fed only corn-soybean meal. Furthermore, the analysis concluded that the dried bakery waste was homogeneous, according to the performance and nutrient analysis of the broilers. Al-Tulaihan et al. [47], found that the addition of up to 30% dried bakery waste resulted in live weight, FCR and feed consumption that were similar to those of 42-day-old broilers fed only corn-soybean. It was reported that dried bakery waste, obtained from local bakeries, can be used to replace part of the corn in broiler rations without adversely affecting performance.

Al-Ruqaie et al. [49] reported that replacing up to 100% of dietary maize with BW reduced the total feed and feed cost to produce 1 kg of live weight without compromising performance, nutrient utilisation and carcass characteristics of broiler chickens. Yadav et al. [50] show that the inclusion of up to 40% dried bakery waste in broiler diets does not negatively affect the economic feasibility of broiler production. A recent study [51] showed that replacing up to 40% of maize with bakery waste in broiler diets is a cost-effective strategy that does not adversely affect growth performance. However, carcass evaluation showed that while overall carcass traits were unaffected, eviscerated carcass and breast yields were significantly lower ($p < 0.05$) in broilers fed bakery waste diets. This suggests possible nutritional imbalances, particularly in amino acid composition. These may have influenced muscle deposition and fat distribution. In addition to understanding how bakery waste affects protein utilisation and fat storage, further studies on nutrient digestibility and metabolism are needed [51]. A study concludes that dry bakery waste can be used as an alternative to maize up to 60% of the broiler diet to give comparable growth performance and higher profits [52]. Replacing 5 and 10% of wheat with body weight (BW) in quail diets had no adverse effects on body weight gain (BWG), feed intake and FCR, according to Lukanov et al. [53].

Gupta et al. [54] reported that up to 20% of the maize can be replaced with bakery waste for the formulation of all quail (Coturnix japonica) groups, which performed similarly in terms of body weight gain, feed conversion ratio and protein efficiency ratio. Statistically similar results were also obtained for blood biochemical parameters, carcass trait yield, small intestine micrometry and sensory traits. It was concluded that the maize flakes in the quail diet can be safely replaced by up to 20% of BW without any negative effects on the diet. Bakery waste has no other specific use and is cheaper than maize. Tiwari et al. [43] revealed that without any adverse effect on feed intake, FCR and BWG, up to 75% of maize could be replaced by bakery waste. Similarly, the inclusion of bakery waste in pig feed, where it is abundant, reduces the cost of pork production and helps to improve the livelihoods of pig farmers.

Additionally, the phytate-bound phosphorus (P) content in bakery flour is comparatively lower than that found in corn. This is probably a result of the predominant use of wheat in the production of food products used in the production of bakery flour. Wheat has been shown to contain a higher proportion of non-phytate-bound P compared to corn. Bakery products are derived from foodstuffs intended for human consumption, which have undergone various processing techniques such as fermentation, steaming, cooking or baking [40]. This approach serves to eliminate disadvantages such as nutritional variability between batches of food waste, packaging materials and possible contamination from bacteria [7].

Shittu et al. [55], reported that for the formulation of economical broiler rations, an inedible, cheaper bakery by-product, biscuit dough, could replace up to 15% of the costly maize in conventional diets. Broiler performance and profitability can be improved by using biscuit dough in the diet. The level of biscuit dough in the diet can also be up to 15%. A study by Adeyemo et al. [56], found that biscuit waste could be

used as a feed for broilers up to a 50% replacement level for maize in the starter and finisher phases, without compromising the performance and carcass value of the broilers.

Nutrients such as energy, crude protein and crude fibre are of particular importance in the formulation of broiler and layer diets. Consequently, when evaluating the utilisation of food waste products in chicken diets, a nutritional composition analysis is imperative. A diet that is well-formulated, based on the needs of the animal in question and the nutritional analysis of the ingredients in the feed, has been found to lead to an increased feed conversion ratio in animals. As demonstrated in numerous studies, the performance of broilers fed different percentages of food waste was shown to be significantly similar to that of those fed a regular diet of corn and soybeans [39, 45, 47]. The incorporation of a substitute ingredient into poultry diets has the potential to influence the physiological status and growth of poultry. The post-hatching period in poultry is a critical time for the growth of muscle and bone tissue, and it is imperative that this process is supported by high levels of nutrients [39].

In general, the researchers reported no significant difference in cholesterol levels in chickens fed bakery waste compared to those fed a maize-soya-based basal diet [52, 57–59]. Chauhan et al. [60] indicate that, without any adverse effects on the blood biochemistry and immune status of broilers, bakery waste can be used as a substitute for up to 20% of maize in broiler rations. However, significantly higher cholesterol levels were reported in birds fed 100% bakery waste as a maize replacement in broiler rations by Ahaotu et al. [61]. These differences may be explained by the fact that higher levels of bakery waste (50 and 100%) were used in the diets, and their bakery waste source contains a higher EE content (17.14%).

The results of a trial investigating the usability of corn flakes waste as an energy source in broiler diets are displayed in **Table 5** [24]. In the initial phase of the

Cornflakes waste level*	**0**	**20**	**40**	**60**	**100**	**SEM**
Starter, 0–35 day						
DM*	58.41^{a}	74.83^{a}	63.90^{ab}	63.79^{ab}	76.82^{b}	3.08*
CP*	61.00^{a}	70.35^{b}	67.28^{a}	65.07^{a}	74.73^{b}	4.38*
CF*	22.50^{a}	28.41^{b}	26.81^{ab}	25.47^{ab}	27.82^{b}	4.19*
EE*	53.00^{a}	58.66^{b}	54.15^{ab}	56.58^{ab}	59.25^{b}	44.6*
NFE*	72.94	73.96	77.24	71.86	74.22	2.86^{NS}
Finisher, 36–63 day						
DM*	76.31	76.43	78.44	78.16	78.13	1.57^{NS}
CP*	63.59^{a}	68.84^{ab}	68.28^{ab}	71.38^{ab}	74.00	2.41*
CF*	42.69	45.36	48.30	47.61	49.61	4.63^{NS}
EE*	74.52	74.87	71.01	74.86	74.43	2.64^{NS}
NFE*	83.05	86.43	86.70	83.55	83.96	2.33^{NS}
BW at starter, g	1033.33^{a}	1058.33^{ab}	1004.42^{ab}	1125.42^{b}	1014.44^{a}	78.5
BW at finisher, g	2333.2	2177.78	2111.13	2277.78	2975.25	26.1

*DM: Dry matter, CP: Crude protein, EE: Ether exract, CF: Crude fibre, NFE: Nitrogen-free extract, BW: Body weight, *: %, ^{a,b}: Means denoted by the different alphabetical are significantly different ($P<0.05$), NS: Not significantly different ($P>0.05$),$^{\pm}$ SEM: Standard error of means.*

Table 5.
Performance, apparent nutrient digestibility of broilers fed cornflakes waste diets.

experiment, it was observed that the subjects fed with a blend of 80% corn and 20% corn flakes exhibited higher average live weight when compared to those fed with a mixture containing 40% and 60% corn flakes, respectively. It was observed that broilers fed a diet consisting of 100% corn flakes waste exhibited higher live weight at the finishing stage. However, this difference was not found to be statistically significant ($p > 0.05$). The optimal nutrient digestibility was observed in broilers fed a mixture of 80% corn and 20% corn flakes, with a comparable level of nutrient digestibility being recorded in broilers fed a diet consisting of 100% corn flakes waste [24]. A recent study reported that the addition of multi-enzymes (α-galactosidase, galactomannanase, xylanase and β-glucanase) to bakery and biscuit meals had no significant effect on the nutrient utilisation of pigs [62].

8. Use in ruminant nutrition

Barley grain is the most commonly used cereal in lamb and kid diets, accounting for between 50 and 75% of the dietary DM, according to Obeidat [63]. Compared to the barley grain, the bread by-products are much cheaper (20–40% of the price of the barley grain) and have a similar composition. Examples of this waste include leftover cakes, bread, croissants, biscuits, dough and products past their expiration date. Due to consumer preference, acceptance and business policy, these are not used for human consumption [64]. The chemical content of bakery waste used in animal feed has been shown to vary widely in many previous studies [47]. Several studies have been conducted in which ruminants were fed varying amounts of bread by-products or bakery waste. Bread by-products can replace up to 750 g/kg of whole grain maize in a growing-finishing beef feedlot diet, with no loss of performance or meat quality [65]. Replacing 200 g/kg of dietary barley in DM with bread did not affect the nutrient intake, growth or digestibility of kids, while reducing feed costs, according to Haddad and Ereifej [66].

In addition, Afzalzadeh et al. [67] found that up to 250 g/kg of bakery waste could be included in the diets of growing lambs without affecting their performance, resulting in an improvement in the quality of internal and tail fat. As a more cost-effective option, Salama et al. [68] suggested replacing yellow maize with dried bakery by-products at levels up to 1000 g/kg in lamb fattening diets. Obeidat [63] reported that the effects on feed intake, digestibility, growth performance, carcass characteristics, meat quality and general health of black goat kids were comparable when 50 and 100 g/kg bakery waste were included in the diet. The use of up to 100 g/kg bakery waste on a DM basis can also reduce feed costs. It suggested the partial replacement of barley grain in the diet as an alternative feed for growing kids.

In addition, the inclusion of bakery waste had no effect on blood metabolites, haematological characteristics, liver enzymes or renal function. Blood serum metabolites and haematological parameters, which can be influenced by internal and external factors, are important diagnostic tools for the nutritional status and health of animals. In another study, blood parameters other than total protein, albumin, globulin and blood glucose were not affected by the inclusion of 300 and 600 g/kg bakery by-products on a DM basis [69].

Bakery by-products are leftovers of various bakery products such as bread, rolls, biscuits, cakes, cookies and dough that do not meet consumer freshness requirements or expire [64]. Nutritionally, they can be used as an energy concentrate in cattle diets, with an energy content comparable to conventional cereals [70]. One study reported

that dried bakery flour is a very satisfactory feed for lactating cows. In particular, it has been posited that the subject can act as an energy source, capable of replacing corn and oil in dairy feeds [45]. Bakery waste can be incorporated into sheep diets to promote greater ammonia nitrogen utilisation by ruminal microorganisms without altering intake, nutrient digestibility, nitrogen balance, ruminal pH or volatile fatty acid concentration. However, the concentration of ammonia nitrogen showed a negative linear response in relation to the level of inclusion, in which each increase of 1% of bakery waste promoted a reduction of 0.11 mg/dL in the concentration of ammonia nitrogen. This may be related to increased ruminal energy availability, allowing more ammonia to become available for microbial growth [70]. This reduction in ruminal NH3-N concentration may be related to the increased energy availability for microbial protein synthesis provided by the inclusion of bakery waste in the diet, or to the reduced inclusion of soybean meal in the diet due to the higher CP content of the waste compared to maize meal. Cabral et al. [71] reported that the lower inclusion of soybean meal in diets could reduce the availability of NH3-N for microbial protein synthesis. This is due to the fact that soybean meal protein is intermediate in degradation in the rumen. In general, bakery wastes contain lower levels of starch and fibre, but higher levels of EE and sugars when compared to cereal grains. The increased amount of EE increases the total amount of energy, but may reduce nutrient digestibility, including fibre digestibility, when the total amount of EE in the diet exceeds 6–7% DM. In addition, heat treatment during the baking process can alter the digestibility of certain nutrients, such as starch and protein. This modulates the availability of energy and CP to rumen microbes. In addition, especially when fed at high levels, as in high-yielding dairy cows, changes in the profile and chemical nature of nutrients such as starch, sugars and fat during heating may increase nutrient flux from the rumen and impair post-rumen digestion [64]. The biscuit industry is the food industry branch that produces biscuits, crackers, wafers and cake-type bakery products using soft wheat flour. The production of these foods generates a certain amount of waste material that fails to meet the sensory quality criteria of the products, depending on the ingredients and processing technologies utilised. This waste material is then referred to as "scrap" by biscuit industrialists. The precise proportion of waste material in question remains undetermined; however, it is estimated to range from 1 to 5%, contingent on the specific product [72].

The results of the study conducted by Korkmaz and Soycan Önenç [21] on food waste are presented in **Table 6**. When gas production (GP) amounts in this study are evaluated [21], the highest GP amount was found to be 53.69 ml/200 mg DM in pasta, and the lowest amount was determined as 25.76 ml/200 mg DM in ice cream bran mixture (**Table 6**). Soycan Önenç [73] determined in her study that GP in the most used feed dry meadow (DMD), cotton seed meal (COM), and barley were 39.28, 42.34 and 69.85 ml/200 mg DM. In another study conducted by Abaş et al. [22] in the 24 hour incubation, the GP amounts of barley, wheat, oat, maize and wheat bran have changed as 50.00–72.18, 48.65–75.17, 52.58–68.42, 54.77–77.69 and 32.54–56.59 ml/200 mg DM.

In Korkmaz and Soycan Önenç's study [21], the determined GP amount in pasta and pudding in 24 hours was higher than those determined by Soycan-Önenç [73] for DMD and COM and lower than those determined for barley. The obtained results are used to calculate the digestibility of organic matter and the NEL of feedstuff. When DOM, ME and NEL ingredients with the help of net GP amounts are evaluated, it was determined that amounts except DOM for pasta were 96.00%, 13.84 MJ/kg DM and 7.96 MJ/kg DM, respectively (**Table 7**), were within the values given by Abaş

Sample	3 h*	6 h*	9 h*	12 h*	24 h*
Pasta	1.72 ± 0.38^{b}	15.48 ± 1.52^{bc}	34.25 ± 1.27^{a}	41.15 ± 1.92^{a}	53.69 ± 0.86^{a}
Pudding	0.99 ± 0.28^{bc}	22.57 ± 4.03^{b}	28.68 ± 2.18^{ab}	33.61 ± 4.38^{ab}	45.63 ± 7.63^{ab}
Vegetable soup	0.52 ± 0.00^{c}	12.79 ± 1.37^{c}	25.33 ± 2.00^{b}	28.20 ± 2.15^{b}	40.99 ± 2.63^{b}
Yoghurt soup	3.29 ± 0.17^{a}	13.00 ± 1.31^{c}	23.92 ± 1.68^{b}	29.12 ± 1.38^{b}	35.88 ± 0.79^{bc}
Wafer flour	1.11 ± 0.24^{bc}	13.85 ± 3.64^{c}	22.33 ± 3.28^{bc}	25.84 ± 3.88^{bc}	42.80 ± 2.58^{ab}
Ice cream bran mix	1.42 ± 0.56^{bc}	11.75 ± 1.22^{c}	16.01 ± 2.12^{c}	17.85 ± 2.03^{c}	25.76 ± 1.53^{c}

*Mix: Mixture, $^{a-c}$: Means with different letters in the same columns are statistically significant (P < 0.05). $^{\pm}$ SEM: Standard error of means, h: Hour, *: ml/200 mg in dry matter.*

Table 6.
Gas production amounts in the incubation period.

et al. [22] for wheat (DOM = 64.25–90.97, ME = 9.89–14.10 MJ/kg DM, NEL = 5.99–9.06 MJ/kg DM).

It was found out that GP amounts were lower, but DOM, ME and NEL ingredients revealed a similarity with the findings of Abaş et al. [22]. In addition, DOM values were found to be similar to those determined by Umucalılar et al. [74]. When data obtained for pasta are considered, it was determined that pasta could be used as an alternative to wheat in ruminant rations. Denek et al. [75] determined that *in vitro* NEL and ME values of maize, barley, wheat, rye, oat and triticale were 8.41, 12.90 MJ/kg DM; 8.11, 12.51 MJ/kg DM; 8.23, 12.68 MJ/kg DM;8.30, 12.68 MJ/kg DM; 6.79, 9.90 MJ/kg DM and 8.43, 13.04 MJ/kg DM respectively. Graminae are an important energy source in ruminant rations [74]. Digestibility of barley starch in the rumen is approximately 80–90%, while the value in sorghum and maize is 55–70% [76]. DOM of pasta, pudding, vegetable soup, yoghurt soup, wafer flour and ice cream bran mixture in this study, being determined as 70.37–90.99%, supports the idea that these foods could be used as an alternative to wheat and barley in ruminant rations. Barley, wheat, maize and wheat bran, which are rich in energy, are widely used in ruminant rations. When the data found at the end of this study are considered, it was concluded that pasta, pudding, vegetable and yoghurt soups, wafer meal and ice cream bran mixture can be used as an alternative to the above-mentioned materials [21].

It is known that today quinoa, chia, teff, mung bean and buckwheat are widely used in human nutrition. However, the use of these crops is limited in animal

Sample	DOM*	ME**	NEL**
Pasta	90.99 ± 0.76^{a}	12.31 ± 0.15^{b}	6.68 ± 0.10^{b}
Pudding	71.39 ± 6.78^{b}	9.68 ± 1.20^{c}	5.82 ± 0.88^{cb}
Vegetable soup	91.83 ± 2.33^{a}	11.61 ± 0.46^{b}	6.51 ± 0.30^{b}
Yoghurt soup	70.37 ± 0.71^{b}	9.15 ± 0.14^{cd}	4.91 ± 0.09^{cd}
Wafer meal	72.61 ± 2.29^{b}	15.09 ± 0.45^{a}	8.73 ± 0.29^{a}
Ice cream bran mix	89.89 ± 1.36^{a}	7.8 ± 0.27^{d}	4.01 ± 0.18^{d}

*Mix: Mixture, DOM: Digestible organic matter, ME: Metabolisable energy, NEL: Net energy lactation, $^{a-d}$: Means with different letters in the same columns are statically significant (P < 0.05),),$^{\pm}$ SEM: Standard error of means *: % in dry matter, **: MJ/kg in dry matter.*

Table 7.
Digestible organic matter, metabolisable energy and net energy lactation of samples.

Sample	ESOM*	ME_{ESOM}**	ME_{CNC}	ME_{NDF}	ME_{ADF}**	ME_{ADL}
WQ	94.37 ± 0.09^{a}	2640.6 ± 0.71^{e}	3377.4 ± 2.16^{c}	2936.5 ± 0.22^{b}	3415.9 ± 2.99^{b}	2581.9 ± 1.98^{b}
BQ	82.14 ± 0.15^{f}	2720.4 ± 0.73^{c}	3172.3 ± 3.80^{f}	2800.0 ± 0.07^{e}	3102.7 ± 2.41^{e}	2367.3 ± 2.11^{f}
RQ	85.24 ± 0.10^{e}	2675.9 ± 1.73^{d}	3295.1 ± 2.26^{d}	2918.2 ± 1.78^{c}	3219.0 ± 0.59^{d}	2430.6 ± 6.62^{e}
WC	40.38 ± 0.14^{g}	3302.3 ± 10.33^{b}	3427.1 ± 3.11^{b}	2567.9 ± 2.29^{h}	2445.4 ± 1.81^{g}	1830.7 ± 5.0^{g}
BC	36.60 ± 0.19^{h}	3429.6 ± 22.53^{a}	3752.9 ± 8.36^{a}	2733.1 ± 2.17^{g}	2638.9 ± 1.89^{f}	1603.1 ± 2.28^{h}
Teff	86.24 ± 0.08^{d}	2655.7 ± 0.72^{de}	3188.7 ± 1.38^{e}	2977.9 ± 0.26^{a}	3297.4 ± 1.05^{c}	2447.4 ± 8.03^{d}
MB	92.85 ± 0.17^{b}	2683.2 ± 2.19^{d}	3135.3 ± 6.04^{g}	2903.7 ± 1.06^{d}	3221.0 ± 1.33^{d}	2472.6 ± 7.71^{c}
BW	90.93 ± 0.12^{c}	2605.7 ± 0.46^{f}	3383.4 ± 2.21^{c}	2756.8 ± 1.65^{f}	3423.2 ± 1.36^{a}	2630.8 ± 1.62^{a}
P	0.001	0.001	0.001	0.001	0.001	0.001

WQ: White quinoa, BQ:Black quinoa, RQ:Red quinoa, WC:White chia, BC:Black chia, MB:Mung bean, BW:Buck wheat, ESOM: Enzyme soluble organic matter, CNC:Crude nutrient composition, NDF:Neutral detergent fibre, ADF:Acid detergent fibre, ADL: Acid detergent lignin, ± SEM:Standart error of means,$^{a-h:}$Means with different letters in the same column are statistically significant (P < 0.05),:% in dry matter, **:ME contents were translated into kilocalories, ME:kcal/kg in dry matter.*

Table 8.
Enzyme soluble organic matter and metabolisable energy contents of samples.

nutrition. In a study [33], besides CP contents of white, black and red quinoa being higher than those of gramineae, their EE contents were also high, and this resulted in higher ME values calculated from the ME equation for ruminants according to TSE. The ESOM content, which was determined *via* the cellulase technique, was also found to be high (**Table 8**). Quinoa can be used as an alternative to traditional cereals as an energy source during the early lactation period or fattening period, when ruminants have high energy requirements. Particularly due to their linoleic acid amounts being high, their use in the fattening period, it will affect the meat quality positively. It will enable the meat to be rich in conjugated linoleic acid.

The CA contents of white and black chia being high, reveals that they are rich in minerals (see **Table 3**). At the same time, their CP, EE contents being high, resulted in their ME contents also being high. However, their ESOM contents were found out to be very low. The reason was that NDF, and particularly their ADF were at high level. Their oil content being high may also be effective in heat stress prevention in dairy cattle. When fatty acid components are analysed, linolenic acid being high, will increase the polyunsaturated fatty acids and especially conjugated linoleic acid contents of milk fat. Thus, the functionality of milk will increase. When the results obtained from the research are evaluated together, it is concluded that mung bean is an alternative protein source, and teff and buckwheat are new alternatives to cereals. İkizoglu and Soycan Önenç [33] concluded that quinoa, chia, teff, mung bean and buckwheat, which have passed their shelf life due to damage in their package in supermarkets or storehouses, can be used as an alternative feed source in ruminant animal nutrition.

9. Evaluation of food waste as silage

The moisture content of food waste has been found to vary between 50 and 85%. The process has the consequence of reducing the shelf life of the food, which makes it more difficult to collect and incorporate it into animal feed [6]. In a study, similar to Malhatun Çotuk and Soycan Önenç [28] DM contents of silages increased due to the increase in the amount of wafers. However, the reason for the high DM content of the control group was due to the high DM of the starting materials (37.03% of alfalfa and 98.24% of the crumb wafer) (**Table 9**). Kurtoğlu [77] reported that with the withering up to 37% DM, the desired quality of silage fermentation would be achieved. In the study, the starting DM content of alfalfa with withering increased to 37.03%; therefore, as Kurtoğlu [77] reported, the DM content of the control group silages was also found to be high. However, it is thought that the effect of the wafer may be more pronounced in alfalfa with low DM. In the study determined that the amount of CA decreased in the 40 and 50 groups (**Table 9**) compared to the control group. Şakalar and Kamalak [78] reported that increasing the addition of dried molasses beet pulp to alfalfa reversed the rate of increase of CA due to the CA content of dried molasses beet pulp. The decrease in the amount of CA in the 40 and 50 groups in this study was similar to that of Şakalar and Kamalak [78] and was caused by the low amount of CA in the wafer. In this study, adding 30 g/kg and above crumb wafer to withered alfalfa prevented CP fragmentation, especially in 50 group; the CP amount was found to be 25.79%. Increasing the WSC content with the addition of wafers caused a rapid increase in the *Lactobacilli* counts, lowering the pH and inhibiting proteolysis in low pH silages (4.43–4.67). Proteolytic enzymes can reduce the feed value of the silage material. These enzymes convert protein nitrogen into non- protein nitrogen (NPN)

Wafer level[A]	0	20	30	40	50	P-Value
Item						
DM[B]	36.53 ± 0.13[d]	38.05 ± 0.06[c]	38.38 ± 0.02[c]	39.03 ± 0.06[b]	40.09 ± 0.08[a]	<0.001
pH	5.07 ± 0.03[a]	4.67 ± 0.03[b]	4.63 ± 0.03[b]	4.80 ± 0.06[b]	4.67 ± 0.03[b]	<0.001
WSC*	2.84 ± 0.11[e]	4.15 ± 0.04[d]	5.20 ± 0.08[c]	6.01 ± 0.07[b]	7.74 ± 0.10[a]	<0.001
LA**	32.16 ± 0.13[e]	80.20 ± 0.10[d]	101.03 ± 0.03[c]	111.32 ± 0.11[b]	126.08 ± 0.05[a]	<0.001
NH3-N***	7.70 ± 0.13[a]	7.60 ± 0.11[a]	7.18 ± 0.21[a]	6.10 ± 0.11[b]	4.42 ± 0.10[c]	<0.001
DM loss[B]	0.86 ± 0.03[a]	0.83 ± 0.01[a]	0.72 ± 0.01[b]	0.70 ± 0.01[b]	0.69 ± 0.01[b]	<0.001
OM*	89.31 ± 0.33[c]	89.41 ± 0.10[c]	89.58 ± 0.03[bc]	89.82 ± 0.07[b]	90.18 ± 0.07[a]	<0.001
CA*	10.69 ± 0.33[a]	10.59 ± 0.10[a]	10.41 ± 0.03[ab]	10.18 ± 0.07[b]	9.81 ± 0.06[c]	<0.001
CP*	24.40 ± 0.05[c]	24.35 ± 0.06[c]	25.37 ± 0.04[b]	25.12 ± 0.07[b]	25.79 ± 0.10[a]	<0.001
EE*	3.13 ± 0.06[d]	5.06 ± 0.08[c]	5.32 ± 0.05[c]	5.76 ± 0.08[b]	7.02 ± 0.06[a]	<0.001
CF*	23.86 ± 0.17[b]	21.07 ± 0.13[d]	21.58 ± 0.05[d]	23.19 ± 0.10[c]	25.83 ± 0.14[a]	<0.001
NFE*	37.20 ± 0.18[a]	37.49 ± 0.08[a]	37.31 ± 0.05[a]	36.47 ± 0.01[b]	32.98 ± 0.13[c]	<0.001
NDF*	33.55 ± 0.12[a]	33.67 ± 0.12[a]	31.53 ± 0.07[c]	31.35 ± 0.06[c]	32.79 ± 0.12[b]	<0.001
ADF*	26.19 ± 0.08[b]	23.91 ± 0.10[d]	23.15 ± 0.07[e]	24.69 ± 0.06[c]	27.62 ± 0.09[a]	<0.001
ADL*	5.33 ± 0.13[a]	5.33 ± 0.06[a]	5.08 ± 0.08[ab]	4.51 ± 0.06[c]	4.79 ± 0.06[bc]	<0.001
TMAB	5.98 ± 0.04[b]	6.42 ± 0.14[a]	6.42 ± 0.06[a]	6.27 ± 0.02[ab]	6.11 ± 0.09[ab]	˂0.001
Lactobacilli[C]	5.72 ± 0.07[b]	6.23 ± 0.05[a]	6.23 ± 0.06[a]	6.20 ± 0.08[a]	6.00 ± 0.06[ab]	˂0.001
Yeast[C]	4.20 ± 0.10[b]	4.59 ± 0.06[a]	4.62 ± 0.09[a]	4.68 ± 0.10[a]	4.69 ± 0.05[a]	˂0.001
Mould[C]	ND	ND	ND	ND	ND	—
Enterobacter[C]	ND	ND	ND	ND	ND	—

*DM: Dry matter, WSC: Water soluble carbohydrates, LA: Lactic acid, NH_3-N: Ammonia nitrogen, OM: Organic matter, CA: Crude ash, CP: Crude protein, EE: Ether extract, CF: Crude fibre, NFE: Nitrogen-free extract NDF: Neutral detergent fibre, ADF: Acid detergent fibre, ADL: Acid detergent lignin, TMAB: Total mesophilic aerobic bacteria ND: Not detected, [A]:g/kg wafer, [B]:%, [C]:Colony forming unit/g, *:% in dry matter, **:g/kg in dry matter, ***:g/kg in total nitrogen, [a–e]:Means with different letters in the same line are statistically significant (p < 0.01).*

Table 9.
Chemical compositions of the alfalfa silages.

forms, such as peptides and free amino acids. However, it is known that microbial activity in silage plays a significant role in the degradation of ammonia and amines [79]. In the study, NH_3-N levels decreased significantly by adding 40 and 50 g/kg crumb wafers, indicating that the wafer successfully prevents proteolysis. It has been reported that alfalfa silage causes 85% of the total N in alfalfa to become NPN [79]. Also, when large amounts of proteolysis occur, additional protein supplements may have to be used even if the total CP of the ratio appears sufficient to achieve optimum milk production. Therefore, proteolysis in silage-making can seriously affect the cost of milk production [28]. The EE content was higher in the groups with wafers added than in the control group (**Table 9**). However, the highest value in the 50 group was due to the high amount of added wafers. However, the fact that the wafer contained 23.13% EE in DM explains the increase in EE in the 50 group. In the study, adding 30 and 40 g of the wafer decreased NDF and ADF while adding 50 g increased them (**Table 9**), and this may be related to the fact that the high WSC in the wafer was used together with *Lactobacilli* by yeasts and the relaxant effect of lactic acid (LA) on the cell wall could not be revealed.

The fact that the pH levels of the wafer-added groups are close to each other and above 4.5 also supports this situation. However, in Özaslan's [80] study, it was reported that the cell wall components decreased with the addition of corn syrup, and the silage pH was around 4.22. In silage production, there must be lactic acid bacteria (LAB) in the environment so that the silage material does not deteriorate, and WSC content must be sufficient for them to produce lactic acid [28]. In the study, the addition of wafers showed an encouraging effect on the development of *Lactobacilli* counts (**Table 9**), while the *Lactobacilli* counts increased, the yeast counts increased due to the increase in the wafer level. It is reported that carbohydrate sources activate the proliferation of some anaerobic bacteria, primarily LAB, in silage [81]. The increase in *Lactobacilli* and yeast counts was due to the addition of crumb wafers, a carbohydrate source, as reported by Bolsen et al. [81]. Although an increase in LAB counts is desired in silages, an increase in yeast counts is not desired. However, due to the high WSC content of the added wafer in this study, the yeast counts were increased along with the *Lactobacilli*, which is not an expected result.

10. Conclusion

The utilisation of food waste as animal feed has the dual benefits of providing nutrients to both animals and humans, while simultaneously reducing the amount of waste sent to landfills. It could be argued that this approach represents a model which could be adopted in other contexts. Moreover, recycling food waste in animal feeding can contribute to reducing environmental impact and improving the environmental footprint of livestock production.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 4

Antibiotics in Animal Feeds: Benefits and Risks

Fayyaz Rasool, Shakeela Parveen, Kashif Manzoor, Shahid Mahmood and Amina Ayub

Abstract

Antibiotics have been widely used in animal feeds for decades to promote growth and prevent diseases in poultry, livestock, and aquaculture. Antibiotics play a crucial role in enhancing weight gain, improving feed efficiency, boosting nutrient absorption, modulating gut microbiota, reducing morbidity, and preventing infections, all of which ultimately contribute to higher productivity in animal farming systems. However, the unchecked and widespread use of antibiotics in animal feed over prolonged periods has raised significant concerns regarding environmental safety and public health. This is primarily associated with the development of antimicrobial resistance (AMR) in pathogenic bacteria, which increases their resistance to a variety of antibiotics. Antibiotics function through various mechanisms of action in animals, which can affect their performance and may even lead to the emergence of resistant bacterial strains. Controlled and responsible use of antibiotics, following expert recommendations, is crucial and should be regulated according to the guidelines of the WHO, FAO, and WOAH.

Keywords: gut microbiota, antimicrobial resistance, animal feeds, feed efficiency, prevention of infections

1. Introduction

Antibiotics are naturally occurring or synthetically produced chemotherapeutic agents that destroy or inhibit the growth of bacteria and other microorganisms [1]. The first antibiotic, penicillin, was discovered by Alexander Fleming in 1928. He observed that the mold *Penicillium notatum* (later known as *Penicillium chrysogenum*) secreted a substance named penicillin. He found penicillin to be effective against various gram-positive bacteria, including Streptococcus and Staphylococcus [2]. Penicillin was widely used during and after World War II to treat bacterial infections in civilians and soldiers. Penicillin saved countless lives. The discovery of penicillin laid the foundation for the development of other antibiotics [3]. China is the world's largest producer and supplier of raw materials for antibiotics. Other major contributing countries include the USA, Germany, India, Japan, Switzerland, Italy, South Korea, France, the UK, Russia, Brazil, and Canada [4].

Antibiotics can inhibit bacterial growth or kill bacteria, enhance feed efficiency in aquaculture, poultry, and livestock production, promote growth, and prevent diseases in animal agriculture [5, 6]. Antibiotics have revolutionized animal agriculture by enhancing productivity and ensuring healthier animals. They are administered at sub-therapeutic levels to meet the growing global demand for animal protein, maintain optimal gut health, and reduce mortality rates [7, 8].

Animal feeds are a vital component and play an important role in aquaculture, poultry, and livestock production, providing the necessary nutrients to support reproduction, growth, and overall animal health [9]. Animal feeds consist of grains, minerals, vitamins, protein sources, and other additives, including antibiotics, probiotics, prebiotics, and phytogenics [10, 11]. Antibiotics were initially introduced to combat bacterial infections in animals [5]. Suppressing pathogenic bacteria results in faster growth rates and improved feed conversion ratios, ultimately increasing animal production [12]. Antibiotics are also being administered as growth-promotor [13]. However, frequent and uncontrolled use of antibiotics resulted in development and spread of antibiotic-resistant bacteria, undermining the efficacy of antibiotics in treating human and animal infections [14, 15]. Antibiotic residues in animal-derived food products can lead to adverse health effects, including allergic reactions and disruptions to gut microbiome [16].

The application of antibiotics in human and animal feeds and their impacts have been major concerns for the last three decades [14]. However, this has become a worldwide issue over the past five years due to the widespread occurrence of antibiotic resistance and the emergence of antibiotic-resistant bacteria [17]. These concerns have become critical focus for researcher, to balance the benefits of antibiotics with sustainable livestock practices [18].

2. Categories and classes of antibiotics

Antibiotics have been divided into two major categories such as broad-spectrum antibiotics (effective against a wide range of bacteria) and narrow spectrum antibiotics (effective specific range of bacteria). Antibiotics have been divided into three groups on the basis of their sources including natural antibiotics (derived from microorganisms such as Penicillin and Streptomycin), semi-synthetic antibiotics (chemically modified such as Amoxicillin and Methicillin), and synthetic antibiotics (completely man-made such as Sulfonamides and Quinolones) [19]. Some antibiotics totally kill bacteria known as bactericidal antibiotics (Aminoglycosides, Cephalosporins, and Penicillins), and others only inhibit bacterial growth and allow the immune system to eliminate bacteria, known as bacteriostatic antibiotics (Tetracyclines and Sulfonamides) [20, 21].

Major classes of antibiotics include Beta-Lactams (Penicillins and Cephalosporins), Aminoglycosides (Gentamicin and Streptomycin), Macrolides (Erythromycin and Azithromycin), Quinolones (Ciprofloxacin and Levofloxacin), and Tetracyclines (Doxycycline and Tetracycline) (**Table 1**). Antibiotics are administered by oral route (Amoxicillin and Ciprofloxacin) and intravenous route (Vancomycin and Ceftriaxone). Some are applied through skin or mucous membranes and generally known as topical antibiotics such as Bacitracin and Mupirocin [1, 22].

Classes	Mechanism of action	Examples
Aminoglycosides	Inhibition of protein synthesis (30S ribosome)	Amikacin, Gentamicin, Streptomycin
Ansamycins	Inhibition of RNA polymerase	Geldanamycin, Rifamycin
Beta-Lactams	Inhibition of cell wall synthesis	Carbapenems, Cephalosporins, Monobactams Penicillins (amoxicillin, penicillin),
Chloramphenicol	Inhibition of protein synthesis (50S ribosome)	Chloramphenicol
Fidaxomicin	Inhibition of RNA polymerase	Fidaxomicin
Fluoroquinolones	Inhibition of DNA gyrase and topoisomerase IV	Ciprofloxacin, Levofloxacin, Moxifloxacin
Glycopeptides	Inhibition of cell wall synthesis	Vancomycin, Teicoplanin
Lincosamides	Inhibition of protein synthesis (50S ribosome)	Clindamycin, Lincomycin
Lipopeptides	Disruption of bacterial membrane potential	Daptomycin
Macrolides	Inhibition of protein synthesis (50S ribosome)	Azithromycin, Clarithromycin, Erythromycin
Nitrofurans	Disruption of DNA and other macromolecules	Nitrofurantoin
Nitroimidazoles	Disruption of DNA structure	Metronidazole, Tinidazole
Oxazolidinones	Inhibition of protein synthesis (50S ribosome)	Linezolid, Tedizolid
Pleuromutilins	Inhibition of protein synthesis (50S ribosome)	Lefamulin
Polypeptides	Disruption of bacterial membrane integrity	Bacitracin, Polymyxins (Polymyxin B, Colistin)
Rifamycins	Inhibition of RNA polymerase	Rifampin, Rifabutin
Streptogramins	Inhibition of protein synthesis (50S ribosome)	Quinupristin-Dalfopristin
Sulfonamides	Inhibition of folic acid synthesis	Sulfadiazine, Sulfamethoxazole
Tetracyclines	Inhibition of protein synthesis (30S ribosome)	Doxycycline, Minocycline Tetracycline

Table 1.
Major classes of antibiotics.

3. Use of antibiotics

The basic uses of antibiotics in animals are to treat sick animals (therapeutic use), prevent infections (prophylactic use), and improve feed utilization and production (as growth promoters) [23]. The therapeutic use of antibiotics involves exposing the suspected pathogen to an antibiotic for a short period of time at a dose higher than its minimal inhibitory concentration (MIC). Sometimes, therapeutic treatment involves

providing antibiotics to animals in intensive farming systems through feed or water, which may have doubtful efficacy because sick animals might not eat or drink [24]. Prophylactic treatment involves applying antibiotics to farmed animals in moderate to high doses, either in feed or water, for a defined period of time. As growth promoters, sub-therapeutic levels of antibiotics are generally applied to entire flocks and herds over extended periods of time [13].

Generally, sub-therapeutic levels of antibiotics still exceed the MIC of the target probiotics or bacteria such as *Enterococcus spp*. and *Clostridium perfringens*. The major concern regarding the application of antibiotics is both the types of antibiotics being used and the manner in which they are used [25]. Antibiotics intended for human use should not be applied therapeutically in food-producing animals, as the duration and dosage of these antibiotics are now considered to compromise the efficacy of human antibiotics [26]. Antimicrobials have also been used to prevent the occurrence of diseases, in animal feed at sub-therapeutic doses, to enhance production through improved feed conversion for higher mass, and as growth-promoting agents. These antibiotics must be readily available within the country and are largely produced by feed manufacturers and farmers [11].

3.1 Antibiotic use in animal feeds

Antibiotics are generally incorporated into a variety of animal feeds to control disease and promote growth and health in animals. Antibiotics are being used in poultry, swine, cattle, aquaculture (fish and shrimp), and almost all animals. Commonly used antibiotics in poultry feeds include Tylosin, Bacitracin, and Virginiamycin, swine feeds (Chlortetracycline, Tylosin, and Lincomycin), cattle feeds (Monensin, Lasalocid, and Tylosin), and aquaculture (Oxytetracycline, Florfenicol, and Sulfonamides) [17]. Mostly countries have banned, and some have restricted the use of antibiotics as growth promotor in animal feeds due to health risks associated with antimicrobial resistance. Farmers have advised to use alternative to antibiotics such as probiotics, prebiotics, enzymes, and phytogenics (plant-based feed additives with antimicrobial properties such as oregano oil and garlic) [27]. Mostly antibiotics are being used in animal feeds to improve feed efficiency, promote growth, prevent (prophylaxis) infections, control diseases (metaphylaxis), and treat illness (therapeutic use). Use of antibiotics other than prevention and treatment of diseases causes antimicrobial resistance and residues in animal products (meat, milk, and eggs). Following tables (**Tables 2, 3**, and **4**) show bacterial infections and concerned effective antibiotics used to control these infections in poultry, livestock, and aquaculture [28].

The increasing trend of application of antibiotics in animal production systems caused emergence of antibiotic-resistant bacteria having zoonotic nature that are transmitted to humans via food chains. Increasing frequency in emergence of these antibiotic-resistant bacteria causes failure of treatment, making disease more severe [29]. Chromosomal changes are major factors which result in emergence of antibiotic-resistant bacteria, but mobile genetic elements cause horizontal transmission of resistance determinants [30, 31].

Food is one of the major sources that transfers antibiotic resistance determinants among bacteria. Food preservation strategies also spread antibiotic resistance among food-borne pathogens, resulting in the spread of resistant infections in the community, increased mortality as well as increased treatment costs, treatment failure, and decreased infection control efficacy [32]. Food-producing animals are significant

Diseases	Causative Bacteria	Antibiotics
Chronic Respiratory Disease (CRD)	*Mycoplasma gallisepticum*	Tylosin, Doxycycline, Oxytetracycline, Enrofloxacin
Fowl Cholera	*Pasteurella multocida*	Sulfonamides (Sulfaquinoxaline), Tetracyclines, Amoxicillin
Colibacillosis	*Escherichia coli*	Enrofloxacin, Florfenicol, Amoxicillin, Oxytetracycline
Necrotic Enteritis	*Clostridium perfringens*	Bacitracin, Lincomycin, Tylosin,
Infectious Coryza	*Avibacterium paragallinarum*	Sulfonamides, Erythromycin, Oxytetracycline
Salmonellosis	*Salmonella spp*. (*S. pullorum* and *S. gallinarum*)	Enrofloxacin, Florfenicol, Amoxicillin,
Campylobacteriosis	*Campylobacter jejuni*	Erythromycin, Tetracyclines
Pullorum Disease	*Salmonella pullorum*	Sulfonamides, Tetracyclines, Fluoroquinolones
Botulism	*Clostridium botulinum*	Pencillin
Bumblefoot (Pododermatitis)	*Staphylococcus aureus*	Amoxicillin, Erythromycin, Clindamycin
Ornithobacterium Rhinotracheale	*Ornithobacterium rhinotracheale*	Tylosin, Doxycycline, Amoxicillin

Table 2.
Most effective antibiotics against common bacterial infections and diseases of poultry.

Diseases	Causative Bacteria	Antibiotics
Mastitis (Cattle, Goats, Sheep)	*Staphylococcus aureus*, *Escherichia coli*, *Streptococcus agalactiae*	Penicillin, Cephalosporins (Ceftiofur), Tetracyclines, Amoxicillin
Bovine Respiratory Disease (BRD)	*Mannheimia haemolytica*, *Pasteurella multocida*, *Histophilus somni*.	Enrofloxacin, Tylosin, Florfenicol, Oxytetracycline
Clostridial Disease (Blackleg, Tetanus, Enterotoxemia)	*Clostridium chauvoei (Blackleg), C. tetani (Tetanus), C. perfringens (Enterotoxemia)*	Penicillin, Tetracyclines
Foot Rot (Cattle, Sheep, Goats)	*Fusobacterium necrophorum*, *Dichelobacter nodosus*	Tetracyclines, Sulfonamides, Florfenicol
Leptospirosis (Cattle, Sheep, Goats, Swine)	*Leptospira spp*.	Penicillin, Streptomycin, Tetracyclines
Brucellosis (Cattle, Goats, Sheep, Swine)	*Brucella* spp.	Tetracyclines (Doxycycline) combined with Streptomycin
Swine Dysentery	*Brachyspira hyodysenteriae.*	Tylosin, Lincomycin, Tiamulin
Listeriosis (Cattle, Sheep, Goats)	*Listeria monocytogenes*	Penicillin, Amoxicillin, Tetracyclines
Actinobacillosis (Wooden Tongue)	*Actinobacillus lignieresii*.	Tetracyclines, Streptomycin
Actinomycosis (Lumpy Jaw)	*Actinomyces bovis*	Penicillin, Tetracyclines
Salmonellosis (Cattle, Swine, Sheep, Goats)	*Salmonella spp.*	Florfenicol, Amoxicillin, Tetracyclines

Diseases	Causative Bacteria	Antibiotics
Contagious Caprine Pleuropneumonia (CCPP)	*Mycoplasma capricolum subsp. capripneumoniae*	Tylosin, Oxytetracycline
Erysipelas (Swine, Sheep, Poultry)	*Erysipelothrix rhusiopathiae*	Penicillin, Tetracyclines
Johne's Disease	*Mycobacterium avium subsp. paratuberculosis*	Supportive care as antibiotics are not fully effective
Pink Eye (Infectious Bovine Keratoconjunctivitis)	*Moraxella bovis*	Oxytetracycline, Penicillin (topical)

Table 3.
Most effective antibiotics against common bacterial infections and diseases of livestock.

Diseases	Causative Bacteria	Antibiotics
Vibriosis	*Vibrio spp. (V. anguillarum, V. harveyi, V. vulnificus)*	Oxytetracycline, Sulfonamides, Florfenicol
Columnaris Disease	*Flavobacterium columnare*	Oxytetracycline, Florfenicol
Aeromonas Infections	*Aeromonas hydrophila, A. salmonicida*	Oxytetracycline, Enrofloxacin, Florfenicol
Edwardsiellosis	*Edwardsiella tarda, E. ictaluri*	Oxytetracycline, Sulfadiazine-Trimethoprim
Streptococcosis	*Streptococcus iniae, S. agalactiae*	Amoxicillin, Oxytetracycline, Erythromycin
Furunculosis	*Aeromonas salmonicida*	Oxytetracycline, Florfenicol
Bacterial Kidney Disease (BKD)	*Renibacterium salmoninarum*	Erythromycin
Epitheliocystis	*Chlamydia-like bacteria*	Oxytetracycline
Mycobacteriosis	*Mycobacterium marinum*	Rifampin (rare, under veterinary prescription)
Yersiniosis (Enteric Redmouth Disease)	*Yersinia ruckeri*	Oxytetracycline, Florfenicol

Table 4.
Most effective antibiotics against common bacterial infections and diseases of aquaculture.

source of transfer of antibiotic-resistant bacteria and antibiotic resistance genes from the farm to the consumer's plate. Antibiotic residues also play a vital role in transfer of antibiotic resistance in the environment [33, 34].

3.2 Importance of antibiotics in animal feeds

Basic strategy of use of antibiotics in animal feeds was to combat infectious diseases in livestock, ensuring more consistent production and healthier animals. Beyond disease prevention, currently, farmers and industrialists use antibiotics to improve feed efficiency and increase productivity. Extensive application of antibiotics in animal feeds proved particularly beneficial for rapidly growing human population in reducing mortality rates, improving health of livestock, ensuring consistent supply of animal protein, and meeting the demand for meat, dairy, and poultry products [5, 24].

4. Mechanism of action of antibiotics

When administered through feeds, antibiotics enter digestive system of animal. These antibiotics target specific bacterial processes which are essential for their reproduction and survival inside the animal body. After ingestion, antibiotics are absorbed into bloodstream from stomach and intestine. Antibiotics circulate to tissues and organs to approach the specific target site of bacterial infection [5]. Antibiotics target-specific cellular processes in specific structure in bacteria such as some antibiotics involve inhibition of cell wall synthesis in bacteria (penicillins, cephalosporins, and bacitracin), disruption of cell membranes (polymyxins), inhibition of protein synthesis (tetracyclines, macrolides (erythromycin), and aminoglycosides streptomycin), inhibition of nucleic acid synthesis (quinolones (ciprofloxacin) and rifampin), and inhibition of metabolic pathways (sulfonamides and trimethoprim). Antibiotics inhibit or kill bacteria at the infection site and activate immune system to clear the remnant of the killed bacteria. Kill of bacteria at infected sites subside inflammatory responses and infected tissues heal. Antibiotics are metabolized by the liver and excreted through kidneys [35, 36].

Primary function of antibiotics is to prevent diseases, improve overall productivity, and promote growth. Their mechanism of action includes altering microbial populations in the gut, improving nutrient utilization, and modulating the immune system (**Figure 1**). However, these effects are complex and vary depending on the species and the type of antibiotics [37].

4.1 Effects of gut microflora

Antibiotics influence the function and composition of the gut microbiota animal agriculture. They reduce pathogenic bacteria and suppress harmful microorganisms. Antibiotics decrease gut inflammation and the risk of infections. Antibiotics promote growth of beneficial gut bacteria such as probiotics and other bacteria that aid in health and digestion. Antibiotics maintain microbial balance in gut of animals and also prevent dysbiosis (an imbalance in the gut microbiota). However, misuse and overuse of antibiotics leads to antibiotic resistance (ABR) in gut bacteria, posing risks to both human and animal health [5, 38].

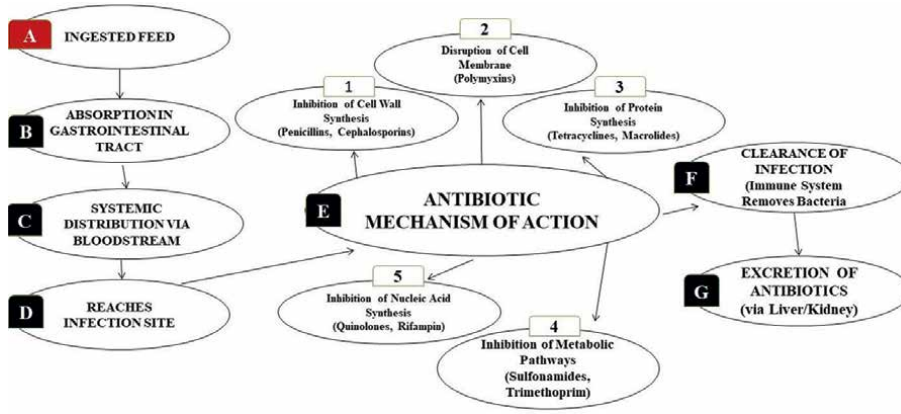

Figure 1.
Flowchart of antibiotic mechanism of action.

4.2 Enhanced nutrition absorption

Antibiotics create a more favorable environment for nutrient absorption, by preventing inflammation and subclinical infections. Antibiotics improve digestion efficiency and ensure more efficient utilization of feed, by reducing the competition between gut microbes and host animals for nutrients. Antibiotics optimize growth rates and lead to higher productivity in livestock, by improving nutrient uptake and supporting better growth performance [39, 40].

4.3 Immune modulation

Antibiotics also play an important role in immune modulation. Antibiotics reduce the energy expended by animals on immune responses and lower immune stress, by controlling inflammation and infections. Antibiotics enhance immunity and stimulate immune pathways, promoting gut health in animals. Antibiotics increase the ability of animals to resist against diseases [10].

5. Benefits associated with the use of antibiotics

Regular supplementation of antibiotics in feed decreases the feed requirement up to 10–15% to achieve a desired level of growth, resulting in decrease of feed cost involved in rearing animals. Antibiotics as feed supplement ensure conversion of feed into improved animal product. The daily growth rate of animals feeding on antibiotic-supplemented food is improved up to 1–10%. The meat quality of such animals is also better with high level of proteins and low lipids [41]. Antibiotics supplementation in poultry feed also increases the production of eggs and their hatchability [42]. Antibiotic-supplemented food also significantly improves the health status of livestock and decreases the rate of diseases surveillance, including chronic respiratory disease and bovine respiratory disease. Antibiotic-supplemented feed also increased body weight gain and decreased the mortality and morbidity rate, resulting in the decrease of disease surveillance [24].

6. Risks associated with the use of antibiotics

Approximately 12 million kg antibiotics is used yearly, of which 75% is used to treat infections and remaining for the purpose of growth and preventive measures [14]. Major portion of 13 million kg antibiotics used in 2010 was used as growth promotor in livestock. Only in USA about 24.6 million pound antibiotics are used as growth promoters in agriculture and animal husbandry rather than treatment of infections [43, 44]. Standard about low dose of antibiotics which can be used as growth promotors for animals and birds set in 1940s. This standard was widely exploited worldwide and currently use of antibiotics as growth stimulator has become global practice [5].

Antibiotic-supplemented feed promotes the emergence of antibiotic-resistant bacterial strains, posing serious threats to human and animal health. World Health Organization (WHO) reported the increased death rate caused by the antibiotic-resistant bacteria when compared to other major diseases including HIV AIDS, during last decade. Residues of antibiotics in animal products and the environment can disrupt ecosystems and affect food safety. Indiscriminate antibiotic usage may weaken the natural immunity of animals, making them more susceptible to infections in the long term [24, 45].

6.1 Development of antibiotic resistance

One of the most critical risks of antibiotic use is the development of antibiotic-resistant bacteria. When antibiotics are overused or misused, they create selective pressure that allows only resistant strains to survive and proliferate [46]. These resistant bacteria can spread among animals, humans, and the environment, leading to infections that are difficult to treat [47]. The rise of multidrug-resistant pathogens, often termed "superbugs," poses a severe challenge to global healthcare systems. These antibiotic-resistant bacteria (ARB), such as Aeromonas, Pseudomonas, Escherichia, Edwardsiella, Flavobacterium, Staphylococcus, Salmonella, Campylobacter, Enterococcus, Clostridium, and Vibrio species pose a significant public health and environmental challenge worldwide. The emergence of resistance occurs when bacteria evolve mechanisms to withstand the effects of antibiotics, rendering standard treatments ineffective. This leads to prolonged infections, higher medical costs, and increased mortality rates [14].

Antibiotics easily kill susceptible bacterial strains, allowing resistant strains to thrive and multiply. Survival of resistant bacterial strains causes emergence of antibiotic resistance genes (ARGs) which are transferred to non-resistant bacteria in the farm environment through horizontal gene transfer and also through mechanisms like transposons, bacteriophages, and plasmids. The emergence of ARGs in aquaculture, poultry, and livestock presents a significant threat to global health, food safety, and environmental sustainability. Manure contaminated with heavy load of antibiotics residues can spread AMR genes to soil and water ecosystems [48].

6.2 Impact on human health

Farmers who rely heavily on antibiotics face many challenges and heavy economic losses due to high mortality and high costs of ineffective drugs. The presence of antibiotic residues in food products such as meat, milk, and fish can directly affect human health. The consumption of food products containing antibiotic residues and AMR genes poses a significant risk to human health by increasing antibiotic resistance, disrupting gut microbiota, the gradual accumulation of resistance genes in humans, and making infections more difficult to treat [49].

Chronic exposure of antibiotics in food animals can transfer these residues, contributing to low-dose resistance in humans. Antibiotic-resistant pathogens of zoonotic nature can be transferred directly to humans through contact with animals, environmental exposure, or consumption of contaminated food [50]. Customers give up use of such products in which antibiotics residues have been suspected including meat, eggs, and milk [51]. Moreover, resistant infections in humans often require longer treatment durations, the use of more toxic drugs, and increased healthcare costs, further compounding the public health burden [52].

6.3 Environmental contamination

Antibiotics used in agriculture and aquaculture often end up in the environment through animal waste, feed runoff, and improper disposal [53]. This contamination can affect soil and water ecosystems, altering microbial communities and promoting the spread of resistance genes among environmental bacteria. The long-term ecological consequences of such contamination include disruptions in nutrient cycling and loss of biodiversity [54].

Excretion of un-metabolized antibiotics from food animals contaminates water and soil. Release of antibiotic residues and pathogenic antibiotic-resistant bacteria from animal farms runoff or manure contaminate local water bodies, affecting aquatic organisms, including fish, insects, and amphibians, and whole aquatic ecosystem. Such practice can cause biodiversity loss. Antibiotics can also harm beneficial microorganisms of soil and water, disrupting nutrient cycles and ecological balance [52].

6.4 Reduction in efficacy of antibiotics

Frequent exposure to antibiotics in non-therapeutic applications, such as growth promotion in animals, reduces the efficacy of these drugs for treating infectious diseases [55]. Over time, pathogens that were once easily treatable with common antibiotics may no longer respond to treatment, limiting therapeutic options for critical conditions in both humans and animals [56].

6.5 Economic consequences

The emergence of resistant bacteria due to antibiotic misuse has significant economic implications [57]. Costs associated with prolonged hospital stays, the development of new antibiotics, and the loss of productivity due to untreatable infections place a heavy financial burden on healthcare systems and the global economy. In agriculture, reduced drug efficacy can lead to decreased productivity and higher mortality rates in livestock, negatively impacting farmers' livelihoods [14].

6.6 Disruption of natural microbiomes

The indiscriminate use of antibiotics can disrupt the natural balance of microbiomes in humans, animals, and the environment. In humans, this may lead to dysbiosis, increasing the risk of infections, metabolic disorders, and immune system malfunctions. In aquatic and terrestrial ecosystems, disrupted microbiomes can affect the health of flora and fauna, influencing ecosystem stability [58, 59].

6.7 Risk of horizontal gene transfer

Antibiotics in the environment can facilitate the horizontal transfer of resistance genes among bacteria through mechanisms like conjugation, transformation, and transduction. This phenomenon accelerates the spread of resistance, making it possible for non-pathogenic bacteria to pass resistance traits to pathogenic counterparts, amplifying the global threat of antibiotic resistance [60, 61].

7. Role of antibiotics in animal feeds

Antibiotics have multiple uses and applications in a variety of disciplines.

7.1 Growth promotion and feed efficiency

Extensive use of antibiotics in sub-therapeutic doses promotes growth in livestock. Antibiotics alter gut microflora, allow beneficial microbes to thrive, and reduce harmful bacterial populations. This mode of action of antibiotics improves

nutrient absorption and digestion and gives better weight gain and feed conversion rates [5]. These actions help farmers by reducing production costs because their low use in feed makes animals grow faster. Such practices exhibited significant improvements in growth rates animal agriculture, including poultry production and aquaculture. Use of antibiotics in intensive optimized productivity, essential to meet market demands [49].

7.2 Disease prevention and control

Antibiotics are basically used as prophylactic agents in animal feed to prevent the outbreak of infectious diseases. In intensive farming system, animals are kept in closed quarters and farms which makes them more susceptible to diseases. Sub-therapeutic doses of antibiotics suppress the growth of pathogenic bacteria, reducing the risks of bacterial infections. For instance, use of sub-therapeutic doses of antibiotics in feed can control the necrotic enteritis in poultry and bovine respiratory disease in cattle. Such approach not only minimizes mortality rate but also reduces the need for high therapeutic doses of antibiotics during disease outbreaks [1].

7.3 Improving livestock production

The combined effects of disease prevention and growth promotion help in improving productivity in livestock and aquaculture. Healthy animals produce higher-quality milk, eggs, and meat and show optimized growth rates, ensuring better yields for farmers. Antibiotics allow farmers to achieve predictable outputs, reducing the variability in production. Such consistency plays an important role for meeting the demands and needs of large-scale commercial markets. Antibiotics also enhance reproductive efficiency and improve the general health and vigor of breeding animals, contributing better offspring and long-term productivity [49].

7.4 Increased livestock productivity

Antibiotics also enhance productivity by improving feed efficiency. Sub-therapeutic doses of antibiotics promote growth and improve overall metabolic performance. Antibiotics improve efficiency of digestive enzymes, minimizing the feed requirement, leading to reduced feed costs. Antibiotics contribute to faster growth cycles, helping farmers to bring animals to market sooner. Use of antibiotics ensures higher yield, utilizing same resources in large-scale farming operations [49].

7.5 Reduction in disease incidence

Normally infections impair growth of animal. Use of antibiotics reduces the prevalence of subclinical infections, suppress harmful microorganisms in gut of animals, and lead to better survival despite environmental changes. Low prevalence minimizes the need for therapeutic antibiotic interventions, saving more expenses of labor [49].

7.6 Economic advantages for farmers

Antibiotics enhance feed efficiency which reduces feed consumption, lowering feed cost and overall expenses. Antibiotics increase profit rate, reducing mortality of animals which enhances production and reduce veterinary costs. Such practice offers

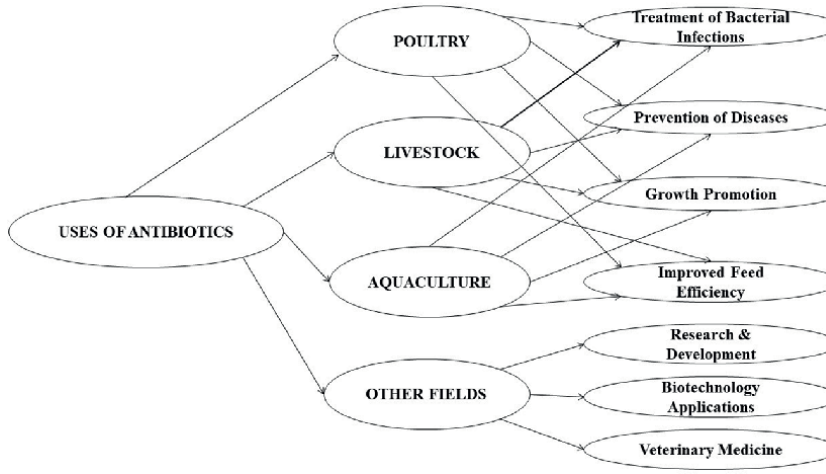

Figure 2.
Flowchart of uses of antibiotics in poultry, livestock, aquaculture, and other fields.

significant financial benefits to farmers. Controlled use of antibiotics in commercial farming gives margin profits to farmers (**Figure 2**) [62].

8. Global perspective on antibiotic use

Researchers and farmers in many countries used antibiotics extensively for the purpose of treatment and prevention of disease. Global health agencies, the World Organization for Animal Health (OIE), the Food and Agriculture Organization (FAO), and the World Health Organization (WHO) have declared antimicrobial resistance (AMR) and forced nations for limited use of antibiotics for non-therapeutic purpose in animal agriculture. These organizations advocate for a "One Health Approach" to address antibiotic use in animals and humans to secure the environment [63].

9. Regulatory frameworks and guidelines

Regulations and guidelines for antibiotic use aim to promote responsible practices while balancing animal health and productivity.

1. *Veterinary oversight*: Many countries require veterinary prescriptions for the use of antibiotics in animals to prevent misuse. Surveillance systems monitor the sale and usage of antibiotics.

2. *Withdrawal periods*: Regulatory bodies mandate withdrawal periods to ensure antibiotics are cleared from animals' systems before their products (meat, milk, and eggs) enter the human food chain.

3. *Antibiotic stewardship programs*: Encourage farmers and veterinarians to adopt judicious use of antibiotics. Promote alternative methods to improve animal health, such as vaccination and enhanced biosecurity.

4. *Harmonized standards*: International bodies like Codex Alimentarius develop guidelines to harmonize food safety standards, ensuring antibiotic residues in animal products remain within safe limits.

5. *Enforcement challenges*: In developing nations, weak regulatory enforcement and lack of awareness remain significant obstacles to effective implementation.

10. Alternative feed strategies

Farmers and researchers must ensure use of probiotics, prebiotics, and phytogenics to make nutritionally balanced feeds to promote health and increase production. Fermented feeds must be incorporated to reduce pathogens and improve gut microbiota. Waste from livestock, poultry, and aquaculture must be recycled into biogas and compost to improve sustainability and reduce environmental contamination. Synergy must be promoted between crop and livestock, poultry, and aquaculture systems [5].

10.1 Probiotics and prebiotics

These feed additives promote gut health and enhance the immune system without contributing to antimicrobial resistance. Probiotics (e.g., *Lactobacillus* and *Bifidobacterium*) suppress the pathogenic bacteria, reduce gut infections, improve digestion, enhance absorption and feed efficiency, and support immune system and overall animal health [64]. Prebiotics are non-digestible food ingredients (e.g., inulin and oligosaccharides). Prebiotics promote bacterial growth in animal's gut, support efficient digestion, and enhance productivity. The combined use of probiotics and prebiotics, termed synbiotics, further amplifies their positive effects [65].

10.2 Phytogenic feed additives

Phytogenics, derived from plants, are gaining popularity as natural growth promoters and immune enhancers. Phytogenics include essential oils (e.g., thyme and oregano), herbal extracts (e.g., garlic and turmeric), spices, and other plant-derived bioactives. Phytogenics have natural antimicrobial effects. These reduce the need for antibiotics, minimize gut inflammation, improve nutrient absorption, enhance feed flavor, and encourage higher feed intake. These are considered and act as friends of environment and best alternative to antibiotics and do not contribute AMR [66].

10.3 Vaccination strategies

Vaccines are a preventive tool that protects livestock from specific diseases, reducing the reliance on antibiotics. Vaccination stimulates animal's immune system, and antibodies are produced to protect against pathogens for longer periods to decrease the risks of major outbreaks. But development of vaccine against a specific pathogen has always been time and cost consuming [67].

11. Success stories from reduced antibiotic use

Several countries and organizations have successfully implemented strategies to reduce antibiotic use in animal farming without compromising productivity or

animal health. Denmark, Netherlands, China, USA, India, and many other countries with major industrial sectors have banned and restricted antibiotics use in poultry, livestock, and aquaculture for growth promotion and feed efficiency purposes [55, 58]. This ban and restricted antibiotics use has resulted healthy and high production. These countries have given strict guidelines to implement and suggested to ensure better biosecurity, hygiene, and use of vaccines, probiotics, prebiotics, and phytogenics. Such practice will save from major economic losses and protection of environment. Such practice will also win the trust of consumers [49].

12. Lessons learned from antibiotic mismanagement

Mismanagement of antibiotics in animal farming has led to severe consequences, providing critical lessons for the global community. Antibiotic mismanagement has taught that misuse fosters antibiotic resistance, threatening global health and rendering treatments ineffective [63]. It highlights the need for responsible stewardship, stricter regulations, and awareness campaigns to prevent overuse. Sustainable practices, including alternatives like probiotics and vaccines, are essential to safeguard antibiotics for future generations [59, 63].

13. Advances in sustainable poultry, livestock, and aquaculture management

Sustainable livestock management focuses on improving productivity while minimizing environmental impact and reliance on antibiotics. Farmers must improve ventilation and housing system to reduce the risk of disease. Integrated pest-parasite management must have adopted to ensure a healthy management at poultry, livestock, and aquaculture. Biosecurity measures must be enhanced to prevent the spread of diseases [62, 64].

14. Innovations in disease prevention

Highly advanced methods have been adapted for disease prevention that reduce dependency on antibiotics while ensuring animal health.

14.1 Next-generation vaccines

Currently, next-generation vaccines have been developed which are highly effective, precise, and specific to target pathogens. Next-generation vaccines include subunit and mRNA-based vaccine. Similarly, autogenous vaccines have been developed and being used to control specific pathogens and outbreaks at farms [61, 62]. Bacteriophage therapy and probiotics are also the best alternatives which are used against specific pathogenic bacteria. Nanotechnology is also innovative alternative used to deliver antimicrobial agents which reduces the quantity of antibiotics [68].

14.2 Role of research and technology

Research projects must be performed to study mechanisms of AMR and its impacts to develop awareness in the public for sensible and responsible use of

antibiotics. Recently, CRISPR-Cas9 technology has been explored to eliminate pathogenic bacteria and to engineer disease-resistant [60, 61]. Research of AMR genes will help to improve the immunity against pathogenic bacteria. Global organizations must collaborate to address AMR and enforce the farmers and researchers to use alternatives to decrease effects of resistance [5].

15. Balancing benefits and risks for sustainable practices

International organizations and local government of each country should enforce farmers and researchers to use antibiotics according to internationally set regulations and guidelines by World Health Organization (WHO), Food and Agriculture Organization of the United Nations (FAO), and World Organization for Animal Health (WOAH) (formerly OIE—Office International des Epizooties). Regular screening of farms is mandatory to use correct antibiotics and avoid their misuse. Farmers must use alternatives of antibiotics such as probiotics, prebiotics, phytogenics, and vaccines [62, 63]. Seminars and conferences must be organized at national level to educate farmers and veterinarians about the correct use of antibiotics. They must be given full knowledge of impact of misuse of antibiotics. Consumers awareness is also mandatory for responsible use of quality animal products. One health approach must be applied, and all the food sectors must collaborate to address AMR. Public and private sector partnership can also play a significant role in eradicating the misuse of antibiotics. Innovative research must be done to develop new technology (genetic and nanotechnology) and strategies to control AMR [5].

16. Future of antibiotics in animal feeds

The future of antibiotics in animal feeds is shifting toward reduced reliance due to growing concerns over antimicrobial resistance (AMR) and its implications for public health and food safety [65, 68]. Advances in science and technology are paving the way for alternative strategies such as probiotics, prebiotics, phytogenics, and immunostimulants to replace antibiotics as growth promoters and disease preventives [64, 66]. Global regulatory frameworks are increasingly restrictive, emphasizing responsible use, while research continues to explore novel feed additives and precision nutrition techniques to maintain livestock productivity [68]. Collaboration between researchers, policymakers, and the agricultural industry will be critical to developing sustainable solutions, ensuring that animal health and food security are achieved without compromising human health [67].

17. Conclusion

The use of antibiotics in animal feeds has long been recognized for its benefits in improving animal growth performance and preventing diseases, but the associated risks, particularly the emergence of antimicrobial resistance (AMR), have raised serious global concerns. To address these challenges, alternative strategies such as the use of probiotics, prebiotics, phytogenics, and immune-boosting additives should be explored and implemented to reduce dependency on antibiotics. Strict adherence to international rules and regulations, such as those established by the World Health

Organization (WHO) and the Food and Agriculture Organization (FAO), is essential to ensure responsible use of antibiotics in livestock. National and regional regulatory bodies should also enforce stringent policies to monitor and control antibiotic usage, coupled with educational initiatives to raise awareness among stakeholders. It is recommended that future research focuses on developing cost-effective and sustainable alternatives, while governments and industries collaborate to support the transition toward antibiotic-free farming systems. By adopting these measures, the livestock sector can mitigate the risks of AMR while ensuring animal health, productivity, and food security for future generations.

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Chapter 5

The Role of Feed Additives in Enhancing Ruminant Performance and Sustainability

Ugur Serbester

Abstract

Feed additives are essential in advancing modern ruminant nutrition by addressing challenges related to productivity, environmental sustainability, and animal health. This chapter explores the diverse roles of feed additives in optimizing rumen fermentation, enhancing nutrient utilization, and reducing methane emissions within evolving global livestock production systems. It provides a comprehensive classification of additives—including buffers, ionophores, probiotics, enzymes, tannins, essential oils, and rumen-protected nutrients—detailing their mechanisms for improving feed efficiency and mitigating environmental impacts. The integration of these additives with nutritional models and emerging innovations such as microbial precision engineering and algae-based solutions is examined. While feed additives demonstrate significant benefits, challenges remain in economic feasibility, regulatory compliance, and global accessibility. Future directions emphasize precision nutrition approaches and the development of scalable solutions to ensure a sustainable livestock sector that meets growing global demand.

Keywords: feed additives, rumen fermentation, methane reduction, nutrient utilization, sustainability

1. Introduction

Ruminants play a crucial role in global food production, contributing significantly to food security and nutrition. The global ruminant sector, including cattle, sheep, and goats, produces approximately 30% of all animal protein consumed by humans, with beef and dairy products being major contributors [1]. According to the Food and Agriculture Organization (FAO), world meat production reached 337 million tons in 2022, with beef accounting for approximately 22% (74 million tons) of this total. Global milk production exceeded 880 million tons, with over 81% coming from cattle [2]. Notably, the demand for animal-derived products continues to rise, driven by population growth, increasing incomes, and urbanization, particularly in developing regions. Projections indicate that global meat consumption will increase by 14% by 2030 compared to the 2018–2020 average, while dairy consumption is expected to grow by approximately 22% over the same period [3].

Despite their importance in global nutrition, ruminant production systems face several sustainability challenges. Environmental impact represents a significant

concern, as ruminants contribute approximately 14.5% of global anthropogenic greenhouse gas (GHG) emissions, with enteric methane (CH_4) accounting for about 44% of livestock sector emissions. A single dairy cow can produce 70–120 kg of CH_4 annually, equivalent to the greenhouse effect of 1.75–3 tons of carbon dioxide (CO_2) [4]. Additionally, ruminant production is associated with nitrous oxide emissions from manure management and land use changes.

Resource utilization presents another challenge, as the livestock sector utilizes approximately 70% of agricultural land globally, including one-third of arable land for feed crop production. With increasing competition for land, water, and grain resources, optimizing feed efficiency in ruminant systems is critical for sustainable resource utilization [5]. Animal health and welfare concerns have also grown, as ensuring optimal health while reducing reliance on antibiotics and growth promoters has become increasingly important for consumers and regulatory bodies. Disease prevention and animal welfare considerations are increasingly integrated into sustainability frameworks for livestock production [6].

Economic viability remains a primary concern for producers facing volatile market conditions and increasing input costs. Rising feed costs, which can represent 60–70% of total production costs in intensive systems, necessitate strategies to enhance feed efficiency and reduce waste [7].

Feed additives have emerged as essential tools in addressing these challenges by improving digestion, enhancing nutrient utilization, and mitigating environmental impacts. They represent a diverse group of compounds that, when added to ruminant diets in small quantities, can significantly modify digestive processes, metabolism, and production outcomes [8]. Through various mechanisms, feed additives can optimize rumen fermentation patterns, enhance nutrient absorption, reduce CH_4 emissions, and improve overall animal health and productivity.

This chapter aims to (i) define the role of feed additives in modern ruminant nutrition within the context of global production demands; (ii) explore the sustainability challenges facing ruminant livestock systems; (iii) provide a comprehensive examination of different types of feed additives and their mechanisms of action; (iv) highlight strategies for enhancing feed efficiency and reducing environmental impacts; and (v) discuss emerging innovations and future directions in feed additive development and application. By synthesizing current knowledge and research on feed additives in ruminant nutrition, this chapter provides insights into how these tools can contribute to more sustainable and productive livestock systems.

2. Types of feed additives for ruminants

Feed additives encompass a diverse range of compounds that can be strategically incorporated into ruminant diets to enhance performance, improve feed efficiency, and reduce environmental impacts. This section provides a comprehensive overview of major categories of feed additives used in ruminant nutrition, detailing their modes of action and practical applications.

2.1 Buffers and pH regulators

In ruminant diets, buffers are primarily used to maintain rumen pH and prevent acidosis. The rumen functions as a complex fermentation system where microbes break down feed into volatile fatty acids (VFAs). However, excessive VFA production,

particularly when feeding high-grain diets, can lower rumen pH and lead to acidosis. Buffers help maintain an optimal pH range (6.2–6.8), ensuring efficient microbial activity and fiber digestion [9].

Buffers commonly used in ruminant nutrition include sodium bicarbonate ($NaHCO_3$), one of the most widely used buffers, which neutralizes excess acidity and stabilizes rumen pH. Research indicates that sodium bicarbonate supplementation at 0.75–1.5% of dietary dry matter (DM) can increase rumen pH by 0.1–0.2 units in high-concentrate diets [10]. Magnesium oxide (MgO) functions as an alkalizing agent, supporting fiber digestion and reducing the risk of subacute ruminal acidosis (SARA). Typically included at 0.25–0.4% of dietary DM, magnesium oxide has a higher neutralizing capacity per unit weight compared to sodium bicarbonate [11]. Calcium carbonate ($CaCO_3$) is often included in dairy cow diets to provide both buffering capacity and calcium supplementation. It is commonly included at 0.7–1.0% of dietary DM [12]. Sodium sesquicarbonate ($Na_2CO_3{\cdot}NaHCO_3{\cdot}2H_2O$), a combination of sodium carbonate and sodium bicarbonate, provides longer-lasting buffering effects in the rumen. Studies show it can maintain higher average daily rumen pH compared to single-component buffers [10].

The efficacy of buffers depends on several factors, including dietary composition, forage-to-concentrate ratio, and animal production level. Buffers are particularly beneficial in high-producing dairy cows consuming energy-dense diets or during dietary transitions when the risk of acidosis is elevated [13].

2.2 Ionophores

Ionophores are antimicrobial compounds that selectively modify rumen microbial populations, altering fermentation patterns to improve energy utilization and reduce CH_4 production. The most commonly used ionophores in ruminant nutrition include monensin, the most widely studied ionophore, which alters ion transport across bacterial cell membranes, inhibiting gram-positive bacteria while favoring gram-negative species. This shifts fermentation toward propionate production, reducing the acetate ratio and decreasing CH_4 formation. Studies demonstrate that monensin can reduce CH_4 emissions by 4–10% while improving feed efficiency by 2–8% [14]. Lasalocid, similar to monensin in its mode of action, modifies rumen fermentation by inhibiting certain bacterial populations. Research indicates it can enhance nutrient digestibility and reduce CH_4 production, although its effects may differ slightly from monensin [15]. Salinomycin, used primarily in beef cattle production, alters VFA production patterns and improves feed efficiency. Studies show it can reduce CH_4 production by 4–8% and improve average daily gain by 2–5% in feedlot cattle [16].

Ionophores exert their effects through several mechanisms, including selective antimicrobial action, where they disrupt ion gradients across cell membranes of gram-positive bacteria, reducing their activity while favoring gram-negative species that produce propionate. They create altered fermentation patterns by shifting fermentation toward propionate production, improving energy capture efficiency, as propionate is glucogenic and energetically more efficient than acetate. Additionally, ionophores reduce protein degradation by inhibiting hyper-ammonia-producing bacteria, decreasing ruminal protein degradation, and improving nitrogen utilization [17].

The inclusion of ionophores in ruminant diets has been associated with multiple benefits, including improved feed efficiency, reduced CH_4 emissions, decreased risk of acidosis, and prevention of certain metabolic disorders. However, regulatory

restrictions on their use exist in some regions, particularly in the European Union, where they are not permitted as growth promoters due to concerns about antimicrobial resistance [18].

2.3 Probiotics and prebiotics

Probiotics and prebiotics enhance the microbial balance in the rumen, improving digestion and fermentation efficiency. Probiotics are live microorganisms that confer health benefits when administered in adequate amounts, while prebiotics are non-digestible compounds that selectively stimulate beneficial microbial populations. Together, they enhance gut microbial stability, improve digestion and fermentation efficiency, and reduce the risk of pathogenic infections [19].

Probiotics in ruminant nutrition include bacterial probiotics, where Lactobacillus and Enterococcus species are commonly used in ruminant diets to stabilize rumen pH, reduce lactate accumulation, and improve fiber digestion. Research shows that Lactobacillus supplementation can increase milk production by 2–5% in dairy cows and improve daily weight gain by 3–8% in beef cattle [20]. Fungal probiotics, particularly *Saccharomyces cerevisiae* (yeast) and Aspergillus oryzae, are the most widely used fungal probiotics. Yeast cultures stimulate cellulolytic bacteria, enhance fiber digestion, and stabilize rumen pH. Meta-analyses indicate that yeast supplementation can increase milk yield by 1.2 kg/day and improve feed efficiency by 3–4% in dairy cows [21].

Prebiotics in ruminant nutrition include fructooligosaccharides (FOS), which are short chains of fructose molecules that selectively promote beneficial bacteria such as Bifidobacteria, enhancing immune function and nutrient absorption [22]. Mannan-oligosaccharides (MOS), derived from yeast cell walls, bind to pathogenic bacteria with type-1 fimbriae, preventing their attachment to the gut wall and supporting immune modulation [23]. Galacto-oligosaccharides (GOS) stimulate beneficial bacteria and improve mineral absorption in the gastrointestinal tract [24].

The combination of probiotics and prebiotics (synbiotics) has shown promising results in ruminant nutrition, offering synergistic benefits for rumen function and animal performance. Recent studies indicate that synbiotic supplementation can improve milk yield by 5–7% and reduce CH_4 emissions by 8–12% compared to individual component supplementation [25].

2.4 Enzymes

Exogenous enzymes play a crucial role in breaking down complex carbohydrates, proteins, and fiber components in feed, improving feed efficiency by increasing nutrient availability from fibrous feeds and enhancing the digestibility of low-quality forages [26]. Key enzymes used in ruminant nutrition include cellulases, which break down cellulose into simpler sugars, aiding in fiber digestion. Research indicates that cellulase supplementation can increase neutral detergent fiber (NDF) digestibility by 3–7% and improve milk production by 1–3 kg/day in dairy cows [27]. Xylanases target hemicellulose to improve the availability of energy. Studies show that xylanase inclusion can enhance fiber digestibility by 5–10% and increase VFA production in the rumen [28]. Amylases enhance starch digestion, improving energy availability from grain-based diets. Research demonstrates that amylase supplementation can increase total tract starch digestibility by 2–5% and milk yield by 1–2 kg/day [29]. Proteases enhance protein breakdown and absorption, supporting growth and milk production. Studies indicate that protease supplementation can improve crude protein digestibility by 3–6% and nitrogen utilization efficiency [30].

Phytases release phosphorus from phytate complexes in plant-based feeds, improving phosphorus availability and reducing phosphorus excretion. Research shows that phytase supplementation can improve phosphorus digestibility by 15–25% and reduce fecal phosphorus output [31].

Factors affecting enzyme efficacy include enzyme stability in the rumen environment, substrate specificity, application method, and dietary composition. Advanced formulation techniques, such as encapsulation and liquid application, can enhance enzyme stability and efficacy in ruminant diets [32].

2.5 Plant extracts and essential oils

Plant extracts and essential oils are secondary metabolites derived from various plant sources that exhibit antimicrobial, anti-inflammatory, antioxidant, and rumen-modulating properties [33]. These compounds offer natural alternatives to conventional feed additives and can significantly influence rumen fermentation patterns.

Tannins are polyphenolic compounds found in various plants, including oak, quebracho, and mimosa. They can be classified as hydrolyzable or condensed tannins based on their chemical structure. Hydrolyzable tannins, primarily found in oak and chestnut, can reduce protein degradation in the rumen, improving bypass protein availability [34]. Condensed tannins, found in legumes like sainfoin and birdsfoot trefoil, bind to proteins, protecting them from ruminal degradation. Research shows they can reduce CH_4 emissions by 10–15% and improve nitrogen utilization efficiency by 8–12% [35].

Essential oils are volatile, aromatic compounds extracted from plants that have antimicrobial and antioxidant properties. Key essential oils used in ruminant nutrition include garlic oil (*Allium sativum*), which contains organosulfur compounds that inhibit methanogenic archaea. Studies demonstrate that garlic oil supplementation can reduce CH_4 emissions by 12–20% without negatively affecting feed digestibility [36]. Cinnamon oil (*Cinnamomum* spp.) is rich in cinnamaldehyde, which selectively inhibits certain rumen bacteria, altering fermentation patterns toward propionate production. Research indicates it can reduce CH_4 emissions by 8–12% and improve feed efficiency [37]. Thyme oil (*Thymus vulgaris*) contains thymol and carvacrol, which exhibit strong antimicrobial activity against gram-positive bacteria. Studies show it can enhance propionate production and reduce CH_4 formation by 5–10% [38]. Oregano oil (*Origanum vulgare*) is rich in carvacrol and thymol; oregano oil modifies rumen fermentation patterns and exhibits antioxidant properties. Research demonstrates it can improve nutrient digestibility by 3–5% and reduce CH_4 emissions [39].

Saponins are glycosides found in plants such as yucca, quillaja, and tea. They form complexes with cholesterol in microbial cell membranes, disrupting membrane integrity and inhibiting protozoa. Research indicates that saponin supplementation can reduce protozoa numbers by 40–60%, decrease CH_4 emissions by 6–12%, and improve nitrogen utilization [40].

The efficacy of plant extracts and essential oils depends on their chemical composition, inclusion rate, diet type, and animal factors. Combination approaches, where multiple plant compounds are used together, often yield synergistic effects on rumen fermentation and CH_4 reduction [41].

2.6 Rumen-protected nutrients

In ruminant diets, rumen-protected nutrients ensure that essential compounds bypass microbial degradation in the rumen and reach the small intestine for

absorption. This technology has revolutionized precision nutrition in ruminants, allowing for more efficient nutrient delivery and improved production outcomes [42].

Rumen-protected amino acids ensure that certain amino acids, particularly lysine and methionine, which are often limiting in ruminant diets due to microbial degradation in the rumen, bypass the rumen and become available for absorption in the small intestine. Rumen-protected methionine supports milk protein synthesis and metabolic processes. Research indicates that supplementation with rumen-protected methionine can increase milk protein yield by 3–7% and improve nitrogen efficiency in dairy cows [43]. Rumen-protected lysine is essential for milk protein synthesis and growth. Studies show that rumen-protected lysine supplementation can enhance milk yield by 1–3 kg/day and improve milk protein content in dairy cows [44]. Rumen-protected histidine has emerging research suggesting it may be limiting in certain high-producing dairy cow diets. Supplementation has been shown to improve milk yield and protein content in specific dietary scenarios [45].

Rumen-protected fats address the issue that lipids are extensively biohydrogenated in the rumen, altering their fatty acid profile. Rumen-protected fats bypass this process, delivering intact fatty acids to the small intestine. Calcium salts of fatty acids, formed by binding fatty acids with calcium, are stable at normal rumen pH but dissociate in the acidic environment of the abomasum. Research shows they can increase milk fat yield by 5–10% and improve energy balance in early lactation [46]. Prilled fatty acids with high melting points remain solid at rumen temperature, resisting biohydrogenation. Studies indicate they can improve energy intake and support body condition maintenance during periods of negative energy balance [47]. Fatty acid amides, formed by reacting fatty acids with amines, resist ruminal degradation. Research demonstrates they can deliver specific fatty acids, such as omega-3 and omega-6, to the small intestine [48].

Rumen-protected vitamins and minerals address the issue that certain vitamins, particularly B vitamins, are extensively degraded in the rumen. Rumen-protected forms ensure these vitamins reach the small intestine for absorption. Rumen-protected niacin supports liver function and metabolism. Studies show that rumen-protected niacin supplementation can improve energy metabolism and reduce the risk of ketosis in transition dairy cows [49]. Rumen-protected choline is essential for lipid metabolism and transport. Research indicates that rumen-protected choline supplementation can reduce liver fat accumulation by 15–25% and improve milk production in early lactation dairy cows [50]. Rumen-protected vitamin B12 supports energy metabolism and hematopoiesis. Emerging research suggests it may improve feed efficiency and metabolic health in high-producing ruminants [51].

Protection technologies for these nutrients include lipid coating, encapsulation with pH-sensitive materials, chemical modification of nutrients, and formulation into matrix systems. Each technology offers specific advantages in terms of protection efficiency, release characteristics, and cost-effectiveness [52].

2.7 Nitrate and sulfate supplements

Nitrate and sulfate supplements represent innovative approaches to reducing CH_4 emissions from ruminants while potentially improving nitrogen utilization efficiency.

Nitrate supplements utilize nitrate (NO_3^-) as an alternative hydrogen sink in the rumen, competing with methanogenesis for hydrogen. The reduction of nitrate to ammonia consumes 8 electrons, effectively capturing hydrogen that would otherwise

be used for CH_4 formation [53]. The mechanism of action involves nitrate being reduced to nitrite and subsequently to ammonia through the pathway:

$$NO_3^- \rightarrow NO_2^- \rightarrow NH_3 \quad (1)$$

This process is more thermodynamically favorable than methanogenesis, diverting hydrogen from CH_4 production [54]. Research demonstrates that nitrate supplementation can reduce CH_4 emissions by 16–22% when included at 1.5–2.0% of dietary DM. A meta-analysis of multiple studies found an average CH_4 reduction of 12% across various production systems [55]. Careful adaptation to nitrate supplementation is essential to prevent nitrite accumulation and methemoglobinemia. Gradual introduction over 2–3 weeks allows for the development of nitrate-reducing bacterial populations [56].

Sulfate supplements, similar to nitrate, can serve as an alternative electron acceptor in the rumen, competing with methanogenesis for hydrogen. The mechanism of action involves sulfate-reducing bacteria utilizing hydrogen to reduce sulfate to hydrogen sulfide:

$$SO_4^{2-} + 8H^+ + 8e^- \rightarrow S^{2-} + 4H_2O \quad (2)$$

This process diverts hydrogen from methanogenesis, reducing CH_4 formation [57]. Studies indicate that sulfate supplementation can reduce CH_4 emissions by 8–12% when included at appropriate levels in ruminant diets [58]. However, excessive sulfate supplementation can lead to hydrogen sulfide accumulation and sulfur toxicity. Careful monitoring of total dietary sulfur is necessary to prevent adverse effects [59].

Combined nitrate and sulfate supplementation has shown additive effects on CH_4 reduction in some studies, with potential CH_4 reductions of 20–30% when properly formulated. However, careful attention must be paid to adaptation protocols and total dietary levels to ensure animal safety and optimal performance [60].

3. Additives and rumen function

3.1 Interaction of feed additives with rumen microbiome

The rumen microbiome consists of a diverse community of bacteria, archaea, protozoa, and fungi that collectively ferment feed components to produce energy and nutrients for the host animal. Feed additives can significantly influence this microbial ecosystem through various mechanisms, resulting in altered fermentation patterns and improved feed utilization [61].

Feed additives selectively promote beneficial microorganisms while suppressing harmful ones, leading to optimized rumen function. Ionophores selectively inhibit gram-positive bacteria such as *Streptococcus bovis* and Lactobacillus species, which produce lactate, while favoring gram-negative bacteria like *Megasphaera elsdenii* and *Selenomonas ruminantium*, which utilize lactate. This shift reduces the risk of acidosis and improves energy utilization efficiency [62]. Probiotics, particularly yeast cultures (e.g., *Saccharomyces cerevisiae*), stimulate the growth of cellulolytic bacteria such as *Fibrobacter succinogenes* and *Ruminococcus albus*, enhancing fiber digestion. Research indicates that yeast supplementation can increase the population of cellulolytic bacteria by 1–2 log units [63]. Plant extracts, including compounds like saponins,

selectively inhibit rumen protozoa, reducing CH_4 emissions and improving microbial protein synthesis. Studies show that saponin-containing plants can reduce protozoal counts by 40–60% [64].

Certain additives stimulate enzymatic activities within the rumen, improving substrate breakdown and nutrient availability. Exogenous enzymes, such as fibrolytic enzymes like cellulases and xylanases, work synergistically with microbial enzymes, creating a priming effect that enhances fiber degradation. Research demonstrates that enzyme supplementation can increase the fibrolytic activity in rumen fluid by 15–30% [65]. Trace minerals, including copper, zinc, and manganese, function as cofactors for various microbial enzymes, enhancing their activity. Supplementation with chelated forms of these minerals has been shown to improve fiber digestion and microbial protein synthesis [66].

Feed additives can alter the rumen environment to favor certain microbial groups and fermentation pathways. Buffers maintain optimal rumen pH (6.2–6.8), supporting the growth of cellulolytic bacteria that are sensitive to acidic conditions. Research shows that buffer supplementation can increase the abundance of fiber-digesting bacteria by 30–40% in high-concentrate diets [67]. Essential oils, including compounds like thymol and eugenol, possess selective antimicrobial properties, altering microbial competition and fermentation outcomes. Studies indicate that certain essential oils can reduce the population of hyper-ammonia-producing bacteria by 40–50%, improving nitrogen utilization [68]. Electron sink compounds such as nitrates and sulfates serve as alternative hydrogen acceptors, competing with methanogenic archaea and reducing CH_4 production. Research demonstrates that nitrate supplementation can reduce the abundance of methanogens by 20–30% [69].

Advanced techniques such as metagenomics, metabolomics, and real-time PCR have enhanced our understanding of how feed additives interact with the rumen microbiome. These tools allow for precise monitoring of microbial population shifts and functional changes in response to different additives, facilitating the development of more targeted intervention strategies [70].

3.2 Effects on rumen fermentation patterns and volatile fatty acid production

Feed additives significantly influence rumen fermentation patterns by modifying microbial activity, substrate availability, and fermentation pathways. These alterations in fermentation dynamics directly impact VFA production, which represents the primary energy source for ruminants [71].

Different feed additives can shift the proportions of major VFAs (acetate, propionate, and butyrate), affecting energy utilization efficiency and production outcomes. Propionate-enhancing additives like ionophores and fumaric acid increase propionate production at the expense of acetate, improving energy capture efficiency. Research shows that monensin supplementation can increase propionate proportion by 10–20% and reduce the acetate ratio from 3.5:1 to 2.5:1 [72]. Acetate-promoting additives, including certain buffers and fibrolytic enzymes, maintain or enhance acetate production, supporting milk fat synthesis in dairy cattle. Studies indicate that sodium bicarbonate supplementation can increase the acetate proportion by 3–5% in high-concentrate diets [73]. Butyrate-stimulating additives such as prebiotics like FOS promote butyrate-producing bacteria, enhancing rumen epithelial development and nutrient absorption. Research demonstrates that prebiotic supplementation can increase butyrate proportion by 5–15% [74].

Feed additives can influence the total production of VFAs, affecting overall energy availability to the host animal. Enhanced VFAs production results from enzymes, probiotics, and certain plant extracts that improve substrate degradation, leading to increased total VFA concentration. Meta-analyses show that fibrolytic enzyme supplementation can increase total VFA concentration by 5–12% [75]. Regulated VFA production occurs when buffers stabilize fermentation rates, preventing rapid VFA accumulation and acidosis while maintaining optimal total VFA levels for efficient energy utilization [76].

Feed additives also affect the production of fermentation gases, which represent energy and nutrient losses from the system. Methane reduction compounds like nitrates, sulfates, and certain plant extracts reduce CH_4 production by diverting hydrogen toward alternative pathways. Research indicates that 3-nitrooxypropanol (3-NOP) supplementation can reduce CH_4 production by 25–30% without negatively affecting VFA production [77]. Carbon dioxide alteration occurs with some additives that influence CO_2 production, affecting rumen buffering capacity and gas dynamics. Studies show that high-fat supplements can reduce CO_2 production by altering fermentation pathways [78]. Hydrogen utilization is enhanced by alternative electron acceptors that capture hydrogen into reduced end products, improving energy recovery. Research demonstrates that fumarate supplementation can increase propionate production through hydrogen utilization, reducing energy losses [79].

Feed additives can significantly impact nitrogen cycling in the rumen, affecting protein degradation, ammonia formation, and microbial protein synthesis. Reduced protein degradation results from tannins and essential oils that can decrease protein degradation rates, increasing rumen-undegradable protein flow to the small intestine. Studies show that condensed tannins can reduce protein degradation by 20–30% at moderate inclusion levels [80]. Improved nitrogen capture occurs when probiotics and prebiotic compounds enhance microbial protein synthesis efficiency, reducing ammonia losses. Research indicates that yeast culture supplementation can improve microbial nitrogen capture by 5–10% [81]. Ammonia utilization is enhanced by synchronizing carbohydrate and protein degradation through strategic additive use, which improves ammonia incorporation into microbial protein. Studies demonstrate that combining rapidly fermentable carbohydrates with slow-release nitrogen sources can improve nitrogen utilization efficiency by 10–15% [82].

3.3 Strategies to enhance feed efficiency

Feed efficiency represents a critical metric in ruminant production, reflecting the animal's ability to convert feed inputs into valuable outputs such as meat, milk, or fiber. Feed additives play a pivotal role in optimizing this efficiency through various mechanisms and strategic applications [83].

Improving the breakdown and absorption of nutrients represents a fundamental approach to enhancing feed efficiency. Exogenous enzymes, including the application of enzyme cocktails containing cellulases, xylanases, and amylases, improve fiber and starch digestion. Research indicates that fibrolytic enzyme supplementation can increase NDF digestibility by 3–8% and improve feed efficiency by 4–7% [84]. Surfactants and emulsifiers enhance the interaction between digestive enzymes and substrates, improving digestion kinetics. Studies show that non-ionic surfactants can increase fat digestibility by 5–10% and improve nutrient absorption [85]. Physical processing techniques, when combined with feed additives and appropriate processing methods (e.g., steam flaking, extrusion), enhance their efficacy. Research

demonstrates that enzyme application on steam-flaked grains can improve starch digestibility by 8–12% compared to enzyme application alone [86].

Ensuring efficient utilization of absorbed nutrients is essential for maximizing productive outputs. Rumen-protected nutrients, including strategic supplementation with rumen-protected amino acids, fatty acids, and vitamins, improve nutrient utilization at the tissue level. Studies show that balancing amino acid profiles with rumen-protected methionine and lysine can improve nitrogen efficiency by 10–15% in dairy cattle [87]. Metabolic modifiers such as compounds like chromium propionate and carnitine enhance metabolic efficiency and nutrient partitioning. Research indicates that chromium supplementation can improve glucose utilization efficiency and increase milk production by 2–5% in dairy cows [88]. Antioxidants, including selenium, vitamin E, and plant-derived antioxidants, protect tissues from oxidative damage, improving overall metabolic efficiency. Studies demonstrate that organic selenium supplementation can enhance immune function and productive performance during stress periods [89].

Fine-tuning rumen fermentation processes is critical for maximizing energy capture and minimizing losses. VFA profile manipulation through additives that shift fermentation toward propionate production improves energy utilization efficiency. Research shows that monensin supplementation can increase energy retention by 3–5% through propionate enhancement [90]. Methane reduction compounds that suppress methanogenesis reduce energy losses as CH_4. Studies indicate that 3-NOP supplementation can improve feed efficiency by 2–4% through reduced CH_4 production [91]. Synchronization of nutrient release, which matches the degradation rates of carbohydrates and proteins, optimizes microbial protein synthesis. Research demonstrates that synchronized diets can improve microbial protein yield by 10–15% and nitrogen utilization efficiency [92].

Tailoring feed additive strategies to specific animal requirements and production scenarios maximizes their benefits. Phase feeding involves adjusting additive inclusion rates based on production stage and physiological status. Studies show that phase-feeding approaches can improve overall feed efficiency by 5–8% compared to static feeding programs [93]. Individual animal monitoring uses real-time data to adjust additive supplementation based on individual animal responses. Research indicates that precision feeding systems can reduce feed costs by 7–12% while maintaining or improving production [94]. Predictive modeling employs nutritional models to optimize additive combinations and inclusion rates. Studies demonstrate that model-based formulation approaches can improve feed efficiency by 3–6% compared to conventional formulation methods [95].

Combining multiple strategies often yields synergistic effects on feed efficiency. For example, integrating exogenous enzymes with ionophores has been shown to improve feed efficiency by 8–12%, exceeding the individual effects of either additive alone [96].

4. Additives targeting enteric methane production

Enteric CH_4 emissions from ruminants represent a significant environmental concern, contributing approximately 28% of global anthropogenic CH_4 emissions [97]. These emissions result from anaerobic fermentation processes in the rumen, where methanogenic archaea convert hydrogen and CO_2 into CH_4 [98]. Several feed additives have demonstrated potential for mitigating enteric CH_4 production.

4.1 Ionophores

Ionophores like monensin alter microbial populations in the rumen by disrupting ion gradients across the cell membranes of gram-positive bacteria [99]. This shifts fermentation patterns toward propionate production, which serves as a hydrogen sink, reducing hydrogen availability for methanogenesis. Studies have shown monensin can reduce CH_4 emissions by 5–15%, though effectiveness varies with diet composition and adaptation of the rumen microbiome over time [100].

4.2 Plant bioactive compounds

4.2.1 Condensed tannins

These polyphenolic compounds inhibit methanogen activity through protein binding and direct antimicrobial actions [101]. Sources include legume forages such as sainfoin and birdsfoot trefoil. Methane reduction potential ranges from 10 to 30%, depending on concentration and structure [102].

4.2.2 Essential oils

Compounds such as thymol, carvacrol, and eugenol possess antimicrobial properties that can inhibit methanogen growth [103]. Garlic derivatives containing organosulfur compounds have shown particular promise, with allicin demonstrating potent anti-methanogenic effects in vitro. In vivo studies have reported 10–25% reductions in CH_4 yield [56].

4.2.3 Saponins

These glycosides, found in plants like *Yucca schidigera* and *Quillaja saponaria*, suppress protozoa populations that have symbiotic relationships with methanogens [55]. By reducing protozoal numbers, hydrogen transfer to methanogens decreases, inhibiting CH_4 formation.

4.3 Synthetic compounds

4.3.1 3-Nitrooxypropanol (3-NOP)

This novel compound specifically inhibits methyl-coenzyme M reductase, a critical enzyme in the final step of methanogenesis [104]. Field trials have consistently demonstrated 20–40% reductions in enteric CH_4 without compromising animal productivity [105]. 3-NOP has emerged as one of the most promising CH_4 mitigation strategies due to its specific mode of action and consistent efficacy [106].

4.3.2 Halogenated compounds

Bromochloromethane and chloroform act as analogues to coenzyme M, inhibiting methanogenesis [107]. Despite high efficacy (up to 60% reduction), concerns regarding their environmental persistence, ozone depletion potential, and animal health effects have limited practical application [108].

4.4 Alternative hydrogen sinks

4.4.1 Fumaric and malic acid

These organic acids serve as alternative hydrogen acceptors in the rumen, competing with methanogenesis pathways [109]. By redirecting hydrogen toward propionate production, they can reduce CH_4 formation by 5–15% while potentially improving feed efficiency.

4.4.2 Nitrate and sulfate

These compounds act as terminal electron acceptors that outcompete methanogens for hydrogen [16]. Nitrate supplementation has demonstrated CH_4 reductions of 15–30%, though careful dose management is crucial to prevent nitrite accumulation and methemoglobinemia [110].

4.5 Microbial interventions

4.5.1 Direct-fed microbials

Certain yeast strains (particularly *Saccharomyces cerevisiae*) can modify fermentation patterns and enhance fiber degradation, indirectly reducing CH_4 yield [108]. Acetogenic bacteria capable of converting hydrogen and CO_2 to acetate represent a promising approach to compete with methanogens for substrate [111].

4.5.2 Bacteriocins

These antimicrobial peptides produced by certain bacteria can selectively inhibit methanogens [105]. Bovicin HC5 and nisin have demonstrated anti-methanogenic effects in vitro, with research focusing on delivery systems for consistent rumen activity.

4.6 Microalgae supplements

Marine algae containing bromoform compounds, particularly *Asparagopsis taxiformis*, have emerged as potent CH_4 inhibitors [106]. Studies have reported CH_4 reductions exceeding 80% at inclusion rates of 0.5–2% of DM intake [107]. Challenges include commercial-scale production, bromoform stability in feed, and potential impacts on meat organoleptic properties.

5. Integrating additives with feeding models

Integrating feed additives with advanced nutritional models is essential for achieving optimal ruminant health, productivity, and sustainability. Nutritional guidelines, such as those provided by the National Research Council (NRC, 2001) and the National Academies of Sciences, Engineering, and Medicine (NASEM, 2021), play a pivotal role in evaluating the efficacy of feed additives. These models not only predict the nutrient requirements of ruminants across various production stages but also assess the impact of additives on rumen fermentation, nutrient absorption, and

overall feed efficiency. By incorporating such models, producers can ensure targeted and precise use of additives, aligning with both the nutritional demands of the animals and economic goals.

The integration of feed additives should be tailored to the production level of the ruminants to maximize their benefits. For low-producing ruminants, the focus is primarily on enhancing the digestibility of fibrous feeds and providing basic nutrient supplementation to meet maintenance requirements without over-supplying energy or protein. Medium-producing ruminants can benefit from incorporating additives like enzymes and probiotics, which boost microbial efficiency, improve fiber digestion, and support increased productivity without compromising nutrient balance. High-producing ruminants require a more sophisticated approach, involving the use of rumen-protected nutrients such as amino acids and fats, as well as buffers and targeted feed additives that support high metabolic demands. These strategies ensure that the animals receive adequate nutrition to sustain peak production levels while maintaining health and reproductive efficiency.

Predictive modeling offers advanced tools for optimizing the inclusion rates of additives, enhancing their efficacy through data-driven adjustments. By analyzing rumen microbial responses, digestibility coefficients, and feed conversion ratios, producers can fine-tune additive usage to maximize performance while minimizing waste. Models also facilitate the economic evaluation of additive applications, allowing producers to assess the cost-benefit ratio and prioritize interventions that offer the greatest return on investment. Additionally, these models provide insights into how additives influence not only productivity metrics but also environmental sustainability outcomes, such as reduced CH_4 emissions and improved nitrogen utilization.

Modern technologies, such as real-time monitoring systems and precision farming tools, can further enhance the integration of feed additives within nutritional models. By leveraging sensors and data analytics, producers can monitor changes in animal performance and rumen activity, enabling dynamic adjustments to feeding strategies. This adaptive approach ensures that feed additives are used efficiently, addressing individual animal needs and responding to fluctuations in environmental conditions or feed quality. Combining these innovations with established nutritional models like NRC and NASEM creates a powerful framework for sustainable and precision-driven livestock management.

6. Practical applications and challenges

The development of innovative feed additives is transforming livestock nutrition, offering novel solutions to enhance productivity and sustainability. A key area of advancement is microbial precision engineering, which involves the design of tailored probiotics to optimize rumen function. These specialized probiotics target specific microbial populations, enhancing fermentation efficiency and nutrient utilization while supporting animal health. Similarly, encapsulated phytogenic compounds represent a significant step forward in additive technology. By improving the stability and efficacy of plant-based additives, encapsulation ensures these compounds reach their target site within the digestive system, providing consistent benefits. Additionally, algae-derived compounds, including seaweed extracts, are gaining attention for their dual role in reducing CH_4 emissions and enriching animal diets with essential nutrients like omega-3 fatty acids.

Technological advancements are playing a transformative role in the development and application of feed additives. Artificial intelligence (AI) is now being utilized to enhance feed formulation, with machine learning models predicting the efficacy of various additives based on animal-specific needs and production conditions. These predictive capabilities enable more precise and efficient additive selection. Complementing this, smart feed monitoring systems provide real-time tracking of rumen parameters, such as pH and fermentation activity, allowing producers to dynamically adjust additive inclusion rates. Such technologies not only improve feed efficiency but also reduce waste and environmental impact.

While significant progress has been made, there are several areas where further research is needed. One priority is evaluating the long-term effects of feed additives on animal health and productivity, ensuring their sustained efficacy and safety over extended periods. Another crucial area involves exploring the interactions between different feed additives to understand their synergistic and antagonistic effects, which could influence overall feed formulation strategies. Finally, addressing global adoption challenges remains critical. Regional disparities in access to feed additive technologies must be overcome by developing cost-effective solutions and improving knowledge transfer, particularly in regions with limited resources.

7. Conclusions

Feed additives are indispensable in modern ruminant nutrition, offering numerous benefits that bolster productivity and sustainability. By enhancing feed efficiency and nutrient absorption, additives ensure optimal utilization of dietary components, leading to improved growth rates and production outputs. Their ability to mitigate environmental impact, particularly through the reduction of CH_4 emissions, aligns livestock systems with global sustainability goals. Additionally, feed additives support animal health and performance by improving rumen function, digestion, and immune responses, which collectively enhance overall productivity. Despite these advantages, significant challenges remain. Economic viability often poses a barrier, as the cost of certain advanced additives may outweigh their perceived benefits. Regulatory compliance is another hurdle, requiring stringent evaluations to ensure additives meet safety and efficacy standards. Furthermore, consumer acceptance plays a vital role in adoption, with growing demands for transparency and eco-friendly practices influencing additive use.

To fully harness the potential of feed additives, future strategies must focus on integrating advanced formulations with precision nutrition models. This involves using data-driven tools and real-time monitoring systems to tailor additive use according to specific production scenarios and animal needs. Promoting sustainable and scientifically backed applications will foster confidence among producers and consumers alike, ensuring the additives contribute positively to productivity and environmental goals. Collaborative research efforts between industry, academia, and policymakers are essential for driving innovation and addressing existing challenges, such as understanding long-term additive effects and resolving accessibility disparities. By adopting this comprehensive approach, feed additives can continue to play a pivotal role in enhancing productivity while supporting environmental sustainability and economic feasibility within ruminant livestock production systems.

Conflict of interest

The author declares no conflict of interest.

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Chapter 6

Effects of Spray-Dried Plasma in Broiler Chickens

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Abstract

In recent years, the search for alternative feed resources has increased, primarily due to the rise in the prices of protein materials. Spray-dried plasma (SDP) has emerged as a valuable feed additive for broiler production, serving as a natural and effective alternative to antibiotic growth promoters. SDP is a rich source of nutritious substances and has peptides, amino acids, immunoglobulin, albumin, fibrinogen, lipids, growth factors, enzymes, and other components that have specific biological activities. These bioactive compounds enhance growth performance, immune status, and gut health of broiler chickens. This chapter provides a comprehensive discussion on the structure, safety of production, and mechanisms of action of the SDP, with a particular emphasis on its effects under both normal and challenging conditions in broiler chickens. Recent studies have suggested that supplementing broiler diets with SDP at lower dosages over extended periods promotes nutrient digestibility, gut integrity, modulation of inflammatory responses, and reduction in oxidative stress, thereby improving feed conversion ratio (FCR) and overall well-being of broilers. Moreover, the effects of SDP on broilers were more pronounced under challenging conditions than under normal production conditions. Additionally, this chapter evaluates the efficacy of SDP in addressing various production and microbial challenges, establishing it as a biosafe and sustainable component of poultry nutrition.

Keywords: broiler, disease challenge, feed additive, performance, spray-dried plasma, stress condition

1. Introduction

The global demand for white meat, especially poultry, is on the rise due to its relatively lower production costs, shorter production cycles, and superior feed conversion compared to other livestock. This increase is primarily because poultry offers significant nutritional advantages, including high levels of protein, abundant essential amino acids, vitamins, and minerals, rendering it a fundamental component of diets worldwide [1]. Moreover, poultry farming is linked to lower greenhouse gas emissions than other animal protein sources, making it a more sustainable choice in the face of climate change concerns [2]. The growing consumer preference for poultry products highlights the need to optimize broiler production. However, the optimization of

broiler chicken production is influenced by various stresses, which shows the need to refine production techniques to boost output and quality while ensuring the health and welfare of birds. To address these challenges, feed additives have become vital to enhance the performance of broiler chickens. Among these, SDP has gained significant attention because of its ability to improve the growth performance, immune function, and health of poultry.

SDP, derived from animal blood, is characterized by its high protein content and bioactive compounds, which enhance gut health and immune function [3]. Research has demonstrated that SDP improves growth performance, feed efficiency, and intestinal structure in broilers, particularly under challenging conditions [4]. The immune-enhancing properties of SDP are attributed to its abundant immunoglobulins, growth factors, and other bioactive elements that strengthen the immune system and promote digestive health [5]. SDP has demonstrated the capacity to mitigate stress-induced adverse effects by enhancing antioxidant defenses and reducing inflammation in poultry [6]. In addition, SDP has shown potential in modulating the gut microbiome and supporting the immune response, which are crucial for disease resistance [7]. Furthermore, it can serve as a competitive exclusion agent against harmful pathogens, thereby promoting a healthier gut environment for broilers. This multifaceted role of SDP positions it as a valuable alternative to traditional antibiotic growth promoters [8]. This chapter summarizes the nutritional profile of SDP from various sources, outlines the safe production of SDP, explores its mode of action in broiler chickens, and analyzes the effects of recent studies on broiler chickens under both normal and challenging conditions.

2. Methodology

This methodology involved a thorough and up-to-date review of the literature, focusing on studies relevant to SDP, including its production and safety, nutritional composition, mechanism of action, and effects on broilers under both normal and stressful conditions. Studies were selected based on their relevance, research quality, and publication in reputable journals. This chapter offers valuable insights into the potential benefits and limitations of SDP as a sustainable feed additive to enhance broiler production.

3. Spray-dried plasma

Dried plasma is a by-product derived from the blood of animals in slaughterhouses. SDP is derived from the blood of healthy animals [9]. The process involves separating the cellular components of blood, and the plasma undergoes concentration, followed by the final step involving spray drying, resulting in what is termed "spray-dried plasma" [9].

During the slaughter process, it is feasible to obtain 10–15 L of blood from each bovine, whereas porcine animals yield only 2–3 L of blood. Whole blood and plasma comprise 17–18% and 6–8% of crude protein, respectively [10, 11]. Nevertheless, the concentration of crude protein increases when whole blood or plasma undergoes drying and additional processing, transforming it into a protein-rich component for animal-feed formulations. With appropriate collection procedures, sufficient blood can be obtained annually to utilize it in its entirety or its derivatives as a nutritional

source for humans and feed for livestock, poultry, and companion animals [5, 12, 13]. Commonly used blood products for humans and animals are classified as spray-dried animal blood, SDP, spray-dried blood cells, and blood meals (avian, bovine, and porcine). Among these, SDP is widely used as a protein-rich source for animals.

The classification of spray-dried blood products is based on the animal blood source from which it is derived. There are four primary types of plasma: spray-dried chicken plasma (SDCP), which originates from poultry blood; spray-dried porcine plasma (SDPP), obtained from pig blood; spray-dried bovine plasma (SDBP), obtained from cattle blood; and SDP, which is produced from a combination of blood sources from various animals.

4. Production process of spray-dried plasma and biosafety

The production of SDP is a highly controlled process, with regulations implemented to ensure the production of a stable, protein-rich product for application in animal nutrition. The basis of SDP production is strict adherence to hygiene, quality, and safety standards from collection to the end product [14]. The detailed production process is illustrated in **Figure 1**.

SDP manufacturing processes on a commercial scale comply with good manufacturing practices and adhere to stringent quality standards to ensure a safe, high-grade, and pathogen-free product. The process commences with the collection of blood exclusively from healthy animals that have been inspected by veterinarians, using anticoagulants to maintain plasma quality [15]. Blood collection is conducted separately from the meat processing chain to prevent cross-contamination [16]. Through storage and transportation, temperature control is employed to limit microbial growth. The presence of neutralizing antibodies in mixed-species blood provides an additional natural defense mechanism. A critical biosafety feature involves ultraviolet-C irradiation (254 nm, 3000 J/L), which inactivates a broad spectrum of pathogens without compromising the nutritional and functional properties of the plasma proteins [16]. This step is followed by spray drying at 80°C to effectively eliminate bacteria and viruses. The usual inlet air temperatures vary between 170 and 310°C, and the outlet temperature is maintained at ≥80°C, a threshold that assures microbial safety [17, 18]. This controlled drying process rapidly removes moisture, thereby

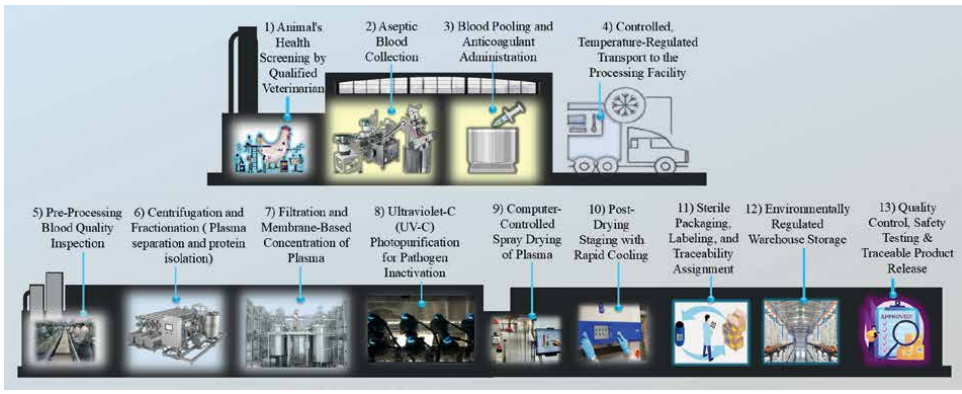

Figure 1.
Key steps involved in the safe production of spray-dried plasma.

transforming the plasma into a shelf-stable powder while preserving its functional and bioactive properties [16]. Further biosafety is achieved through a low final moisture content (~9%) and a 14-day storage period at room temperature, which further inactivates residual microbes [18]. Collectively, these overlapping safety measures ensure the microbiological safety of SDP and its suitability for inclusion in animal feed.

5. Nutritional composition of spray-dried plasma

SDP is a good source of nutrients, especially because of its high protein, essential amino acids, and mineral content. SDP exhibits high dry matter content, ranging from 89.4 to 97.5% depending upon the source, with SDBP demonstrating the highest levels, from 91.8 to 97.5% (**Table 1**). The crude protein content varies considerably among the plasma sources; SDP ranges from 77.95 to 91.17%, SDBP from 70.88 to 79.54%, SDCP from 69.36 to 71.80%, and SDPP from 68.4 to 87.5%. Variations in the protein content are also affected by the production process. Regarding protein composition, albumins and globulins constitute the majority, comprising 95% of the total protein in SDP [9]. Globulins, which represent 40–50% of plasma proteins [38], include gamma globulins that perform immunological functions, with IgG being the most significant functional component in blood plasma. Other immunoglobulin types, such as IgM, IgA, and IgE, are present in smaller quantities in blood plasma [9]. Although SDP has a lower protein content than casein [39], its protein quality, as indicated by its amino acid composition, is relatively high (**Table 2**). SDP contains more essential amino acids compared to soybean meal [39]. It has a higher essential amino acid content than other protein sources [31, 32, 39].

SDP is highly valuable not only for its protein and bioactive components but also for its mineral content. It provides essential macro-minerals, such as calcium, phosphorus, sodium, potassium, chloride, and magnesium, although the concentrations vary among different plasma sources. The ash content exhibits considerable variation across different plasma types. Specifically, SDPP demonstrates a range of 5.00–16.22%, SDCP ranges from 5.52 to 18.28%, SDBP falls between 7.26 and 8.01%, and SDP spans from 8.60 to 15.7% (**Table 3**). Notably, SDBP and SDPP are recognized for their high sodium and chloride contents, while SDPP is abundant in micro-minerals, including iron, copper, manganese, and zinc. The minerals present in SDP demonstrate high digestibility and solubility, thereby enhancing their bioavailability for animal consumption. Although an increased mineral content in SDP may lead to

Item	SDP	SDBP	SDCP	SDPP
Dry Matter (%)	90.85–95.1	91.8–97.5	91.40–95.42	89.4–94.6
Crude Protein (%)	77.95–91.17	70.88–79.54	69.36–71.80	68.4–87.5
Gross Energy (MJ/kg)	21.33	19.5	19.99–20.12	19.1
Ether Extract (%)	0.02–2.60	0.02–1.45	4.02–5.30	0.3–2.5
Ash (%)	8.60–15.7	7.26–8.01	5.52–18.28	5.00–16.22
Reference	[19–24]	[11, 25–27]	[1, 28–30]	[25, 28, 31–37]

SDP: spray-dried plasma, SDBP: spray-dried bovine plasma, SDCP: spray-dried chicken plasma, SDPP: spray-dried porcine plasma.

Table 1.
Nutrient composition of spray-dried plasma derived from various animal sources.

Item	SDP	SDBP	SDCP	SDPP
Arginine	42.1–49.5	38.0–50.0	44.5–49.40	38.0–51.0
Histidine	23.4–26.1	23.0–41.8	18.6–36.60	21.0–32.0
Leucine	70.5–80.1	67.0–101.0	55.7–75.59	62.0–92.0
Isoleucine	27.1–29.0	18.0–33.5	25.5–27.73	20.33–32.0
Lysine	68.7–76.1	61.0–92.0	45.3–68.5	46.0–94.0
Methionine	6.9–10.3	8.6–10.0	16.4–19.6	5.0–11.0
Cysteine	25.9–29.4	12.0–19.0	19.1–26.50	17.9–28.0
Phenylalanine	39.1–44.9	36.0–51.6	32.3–47.4	35.0–45.0
Threonine	43.3–55.4	43.0–66.0	37.4–44.4	36.0–85.0
Tryptophan	13.8–17.0	11.8–19.0	12.8–13.8	13.0–15.0
Tyrosine	37.3–42.6	36.0–47.8	31.4–35.1	10.6–47.0
Valine	50.9–59.7	49.0–70.0	37.7–49.6	9.0–58.0
Alanine	41.1–41.8	39.0–53.0	33.5–49.80	34.9–51.0
Aspartic Acid	73.5–86.0	69.0–107.0	51.70–67.3	62.0–101.0
Glutamic Acid	115.3–119.1	90.0–140.8	67.6–115.4	83.2–140.0
Glycine	27.6	25.0–36.0	26.1–34.0	23.0–33.0
Proline	44.4–45.2	34.0–47.4	33.6–43.2	38.0–59.0
Serine	39.8–52.1	43.0–66.7	41.9–49.9	36.0–65.0
Reference	[21–24]	[11, 25, 27]	[1, 28–30]	[25, 28, 31–36]

SDP: spray-dried plasma, SDBP: spray-dried bovine plasma, SDCP: spray-dried chicken plasma, SDPP: spray-dried porcine plasma.

Table 2.
Amino acid composition of spray-dried plasma derived from various animal sources.

Item	SDP	SDBP	SDCP	SDPP
Macro-minerals (g/kg)				
Calcium	1.5	0.60–10.0	2.1–2.2	0.90–8.5
Phosphorus	15.17–17.1	1.10–13.1	1.7–10.3	1.30–13.0
Sodium	—	24.96–85.0	—	22.0–70.61
Potassium	—	3.30–4.6	—	3.5–13.35
Chlorine	—	36.68–99.3	—	11.0–21.90
Magnesium	—	0.10–0.3	—	0.11–0.30
Micro-minerals (mg/kg)				
Iron	—		—	90.0–998.47
Copper	—	15.0	—	17.0–50.25
Manganese	—	—	—	5.0–11.87
Zinc	—	15.0	—	9.0–79.88
Reference	[21, 22]	[11, 25–27]	[28–30]	[25, 28, 31–33, 36, 37]

SDP: spray-dried plasma, SDBP: spray-dried bovine plasma, SDCP: spray-dried chicken plasma, SDPP: spray-dried porcine plasma.

Table 3.
Mineral composition of spray-dried plasma derived from various animal sources.

adverse effects at elevated plasma inclusion levels, it is possible to reduce plasma ash content through specific technological processes. Additionally, ultracentrifugation can effectively decrease salt content prior to spray drying.

6. Mechanism of action of spray-dried plasma in broiler chickens

SDP contains high levels of bioactive ingredients, including metalloproteins, cytokines, immunoglobulins, albumins, growth factors, hormones, enzymes, bioactive peptides, amino acids, and transferrin [5, 13]. These components enhance broiler chicken performance by enhancing gut health, immune modulation, alleviating oxidative stress, and maintaining the best bone and meat composition [40]. **Figure 2** shows the impact of SDP supplementation on broiler performance, gut health, immune system, and stress resistance. SDP supplementation has been reported to enhance growth performance and feed conversion ratio by enhancing nutrient digestion and absorption [41]. SDP increases the apparent metabolizable energy, dry matter, and organic matter absorption, leading to greater feed intake (FI), body weight gain (BWG), and overall performance. SDP also enhances the digestibility of essential amino acids, such as cysteine, proline, alanine, leucine, threonine, tryptophan, tyrosine, valine, and serine, showing better nutrient absorption, which supposedly leads to better growth performance [42].

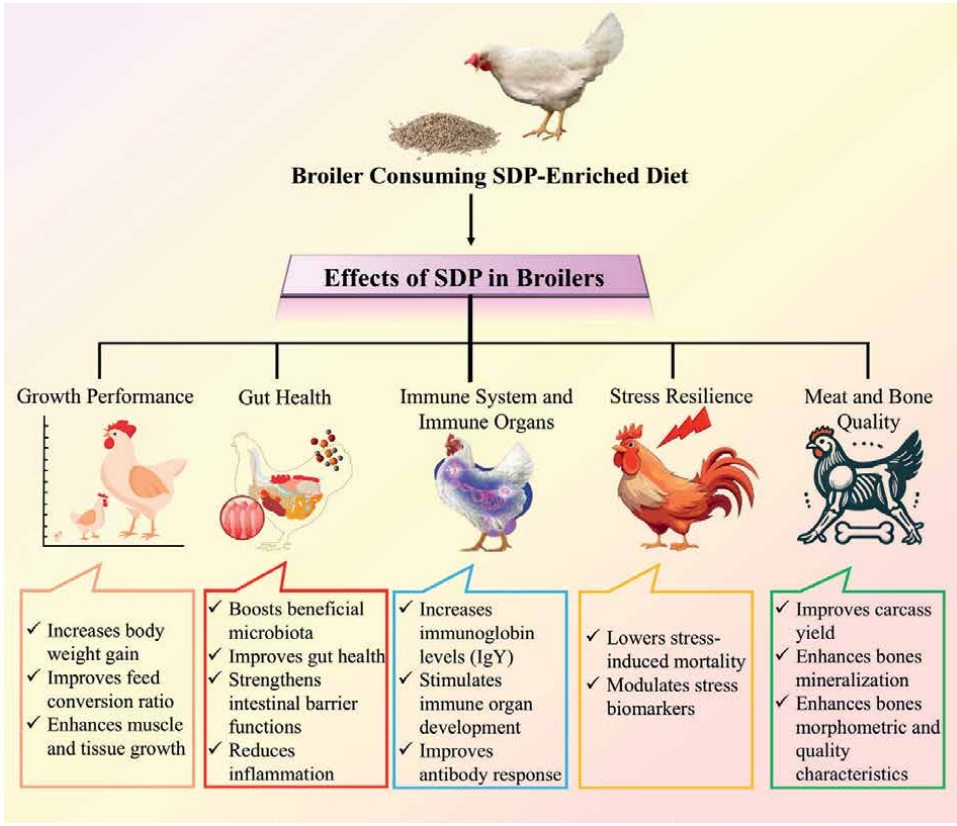

Figure 2.
Effects of spray-dried plasma supplementation on broiler performance, gut health, immunity, bone and meat quality, and stress resistance.

Additionally, SDP maintains gut health by positively modulating the gut microbiota through the enhancement of beneficial bacteria, such as Bifidobacteria, which enrich the intestinal microbiome and improve the utilization of nutrients [41]. The modulation results in enhanced intestinal permeability and intestinal integrity. Moreover, SDP has been found to maintain the gut-associated lymphoid tissue, the largest lymphoid tissue in the body, along with other lymphoid tissues like bronchoalveolar-associated lymphoid tissue and genitourinary-associated lymphoid tissue under the common mucosal immune system. This system protects the gut barrier by inhibiting the invasion of harmful microorganisms and pathogens into the intestinal epithelium. Supplementation with SDP elevates mucosal cytokine levels, enhances the intestinal barrier, and maintains immune homeostasis, thereby preventing the negative effects of external pathogens and promoting general gut health [43]. On the immune system, SDP supplementation has been observed to regulate pro-inflammatory cytokines such as IL-6 and IFN-γ but induces anti-inflammatory effects by enhancing IL-13 upregulation, enhancing the overall immune system, and suppressing inflammation [44]. These immune-enhancing activities are also beneficial for disease control, where SDP has been observed to serve as a natural antibiotic substitute in the treatment of *Salmonella enteritidis* infection in broilers, enabling immune surveillance and gut colonization regulation [7].

In addition to its immune-enhancing properties, studies have confirmed that SDP aids in managing stress. SDP supplementation decreased heterophil counts and increased IgY levels, indicating improved stress resistance. Its high content of immunoglobulins and glycoproteins further protects cells from oxidative stress, helping to maintain an oxidative balance [41]. In a study on the composition of bone and meat, SDP supplementation was found to enhance tibia strength and carcass yield, especially when broilers were fed high-density diets during the starter phase [45]. Furthermore, progeny from breeder hens receiving 1% SDP supplementation showed enhanced bone strength [46]. A previous study demonstrated that SDP exhibited the highest phosphorus digestibility [47]. Nevertheless, some studies have reported that supplementation with SDP does not influence the ash content or retention of calcium and phosphorus within the body [48]. In rapidly growing broilers, tibia development necessitates increased nutrient intake to accommodate their accelerated growth demands, and the addition of SDP can enhance bone development in the early stages without altering mineral content at the finishing stage [45].

7. Effects of spray-dried plasma in non-challenged broiler chickens

SDP has emerged as a valuable feed component in broiler nutrition due to its active bioactive compounds. Over the past two decades, numerous studies have been conducted on the use of SDP in broiler chickens under both normal and challenging conditions. Cost constraints have restricted the extensive adoption of SDP for poultry feed. Nevertheless, the documented advantages of plasma supplementation indicate its potential as a valuable component of poultry production [5]. Consequently, studies have been conducted to ascertain the optimal dosage and duration of plasma supplementation in poultry feed to enhance performance and health.

A study investigating the supplementation of spray-dried colostrum, SDBP, and SDPP in broiler chickens demonstrated that the incorporation of SDBP and SDPP into starter diets from days 1 to 14 elicited beneficial effects on intestinal morphology. Compared to the control group, birds fed SDBP and SDPP diets exhibited increased villus height. Furthermore, chickens receiving the SDPP diet displayed a significant

reduction in crypt depth, while the SDBP supplemented diet did not produce a notable impact on this parameter. Despite these improvements in gut structure, the addition of SDBP or SDPP to the diet did not significantly affect body weight (BW), FI, or FCR during the initial two-week period. Similarly, neither SDBP nor SDPP supplementation influenced growth performance or feed efficiency during the grower-finisher phase (days 14–35) or the overall study period (days 1–35). In addition, supplementation with SDPP and SDBP increased villus height and decreased crypt depth compared with the control group [25]. A study conducted by Jamroz et al. [32] examined the effects of dietary supplementation with 2 and 4% SDPP for a duration of 28 days. The investigators reported no significant changes in BW or FI and mineral composition of bones; however, they observed improved intestinal health and calcium and copper retention in the 2% SDPP-supplemented groups compared to the control group. Further research conducted by Jamroz et al. [48] conducted two broiler studies in which chicks were housed in battery cages and fed 2 and 4% SDP for either 1–28 or 1–30 days. In the initial experiment, the highest BW was attained on day 14 with 4% SDPP. However, by day 28, SDPP had resulted in a decrease in BW. The second experiment demonstrated improved BW on day 30. The FCR in experiment 1 was enhanced for both the 2% and 4% SDPP groups compared to the control during days 1–14. No significant differences were observed in experiment 1 on days 14–28 or in experiment 2 on days 0–30. In addition, the digestibility of essential amino acids (proline, cysteine, valine, histidine, lysine, and arginine) was improved. However, no effects on calcium and phosphorus retention were observed in either experiment; however, jejunum villus height and gut health parameters improved with SDPP supplementation.

A study by Henn et al. [49] examined the effect of SDP supplementation on broiler chicken performance through two distinct experiments with varying dosages and feeding regimens. In the first experiment, broilers were divided into five groups and administered SDP at different levels (0/0/0, 1.5/0/0, 1.5/0.5/0, 3.0/0/0, and 3.0/0.5/0) across three feeding stages (day 1–7, day 8–21, and day 22–42). In the second experiment, four groups were fed alternate SDP dosages (0/0/0, 1.5/0/0, 1.5/0.5/0, and 1.5/0.5/0.25) over three feeding periods (day 1–8, day 9–21, and day 22–42). Findings from experiment 1 revealed that SDP supplementation decreased FI and FCR from day 1 to 21. However, no statistically significant differences were observed in performance parameters during days 22–42 or in carcass and cut yields, livability, and uniformity on day 42. In experiment 2, broilers receiving SDP supplementation demonstrated increased BWG from day 8–21 to day 1–42 when compared to the control group.

In another study, Beski et al. [33] studied the effects of different inclusion levels (0, 1, or 2%) and feeding periods (5 or 10 days) of SDPP on broilers. The results showed an interaction between SDPP concentration and feeding duration at day 10. The highest level of SDPP feeding for a longer period improved BW, lowered FI, and decreased FCR. Feeding SDPP for a longer period further improved FCR and increased the size of the pancreas. Villus height and apparent villus surface area significantly increased with higher levels of SDPP. On day 35, there was a trend toward an increase in BW in birds fed diets containing SDPP. Higher dosing and longer feeding significantly improved the FCR. Researchers have concluded that the use of low-dose SDPP for longer feeding periods can be more economically effective for optimizing the performance of broiler chickens.

A study conducted by Beski et al. [36] investigated the addition of SDPP at 0, 0.5, 1, or 2% in starter diets for 10 days to replace meat meal in wheat- or corn-based broiler diets. SDPP inclusion significantly improved BW and FCR during both the initial 10-day and the entire study period (35 days). On day 10, higher SDPP

concentrations increased the relative organ weights. On day 24, compared with wheat-based diets, the highest dose of SDPP in corn-based diets depressed bursa and spleen weights but increased the pancreatic weight of broilers. SDPP supplementation improved intestinal morphology, as evidenced by longer villi, deeper crypts, and lower villus-to-crypt ratios, irrespective of the grain type. However, on day 35, the SDPP-based diets did not affect dressing percentage or breast muscle yield.

Campbell et al. [50] examined the effects of varying concentrations of SDP (0, 0.75, and 1.5%) in the initial feed of broiler chickens. The investigation involved administering corn-soy-based diets containing different levels of SDP to broilers from days 0 to 14. The data obtained on days 0, 7, and 14 demonstrated that increasing SDP levels resulted in linear improvements in BW, BWG, and FI. The research also revealed that FCR and adjusted FCR decreased linearly, indicating an enhanced feed efficiency at higher SDP concentrations. Notably, the mortality rates remained consistent across all treatment groups. The results of this study demonstrate that starter diet supplementation with SDP improves performance at an early age.

A study conducted by Dabbou et al. [51] investigated the effects of globin and SDPP on broiler chickens from 1 to 40 days of age. SDPP was administered at concentrations of 2, 1%, and 1% during the starter (1–12 days), grower (12–25 days), and finisher (25–40 days) phases, respectively. Compared with the control and globin diets, the SDPP diet significantly increased BW at 12, 25, and 40 days of age. SDPP improved BWG and enhanced FCR, while FI remained unaffected compared to the other two study groups during the entire study period (1–40 days). Neither globin nor SDPP supplementation affected gut morphology, histopathological findings, or lymphoid organs (bursa of Fabricius and spleen) at 12 and 40 days.

Another study assessed the effects of SDP at 0% or 2% inclusion in starter diets for 10 and 21 days on growth performance and nutrient digestibility in a corn-soy-based diet in broiler chicks. BW, FI, and FCR were unaffected by dietary treatments on day 21. However, SDP supplementation significantly improved the digestibility of apparent metabolizable energy, dry matter, and organic matter at both 10 and 21 days. These findings suggest that, while SDP may not influence growth performance, it enhances nutrient digestibility in broiler diets [42].

8. Effects of spray-dried plasma in challenged broiler chickens

Zootechnical stress refers to the physiological and behavioral challenges associated with ambient, managerial, and husbandry practices imposed on broiler chickens. These stresses (high stocking density, poor ventilation, extreme temperatures, feed and water restrictions, handling, and transport) are usually associated with intensive poultry production systems. Understanding and mitigating zootechnical stress is indispensable from the perspective of sustainable and ethical poultry production, as long-term exposure to such stressors compromises not only the health of the birds but also the economic efficiency of the industry. In addition to production challenges, broilers undergo biotic stress (salmonellosis, colibacillosis, mycotoxicosis, necrotic enteritis) during intensive production. These pathogenic challenges decrease production performance, impair gut integrity and health, and affect the health, welfare, and profit margins of production. Antibiotics have been widely used to mitigate the negative effects of these challenges. However, the ban on antibiotic growth promoters in animal feed is coupled with the rise in infectious diseases and public health concerns [52, 53]. Several nutritional strategies have been adopted as alternatives to antibiotics.

SDP has emerged as an effective alternative source of antibiotics. Because of its mode of action that enhances gut health and bolsters the immune system, SDP has been explored as an alternative to or supplement for growth-promoting antibiotics [4]. Studies have demonstrated that SDP supplementation as an alternative to bacitracin methylene disalicylate improved the growth performance, increased the immunity through increasing IgY, decreased the heterophil count, and maintained the oxidative stress [8, 41]. Several studies have been conducted on the supplementation of SDP in different challenges (**Table 4**), and results showed that SDP supplementation has more pronounced results in stressful or challenging conditions.

SDP source	Dose	Challenge	Supplementation duration	Effects	Reference
Production challenge					
SDPP	0, 2%	Clean litter (Exp. 1) Dirty litter (Exp. 2)	0–42 days	Exp.1: No effect on performance and carcass characteristics Exp.2: Increased BWG, FI, and breast meat yield	[3]
SDP	0, 1%	Ventilation pressure	0–10 days	Improved FCR, reduced mortality	[54]
SDP	—	Stocking density	0–4 days	Improved BW, flock uniformity, and decreased lameness	[55]
SDP	1, 2%	Heat stress	0–28 days (2%) 0–42 days (1%)	SDP mitigated the negative effects of heat stress on growth performance, gut permeability, and tibial strength	[56]
SDP	0, 1%	Nutrient density	0–10 days	Increased starter phase growth performance, enhanced tibial quality	[45]
SDP	0, 1%	Stocking density	0–42 days	Improved performance, intestinal health, and tibial bone morphometric parameters	[40]
Biotic challenge					
SDPP	10, 20 g/kg	*Salmonella sofia*	0–14 days	Supplementation improved the nutrients' digestibility, birds' performance, and intestinal health on the 24th day and on the 35th day	[33]
SDP	30 g/kg	*Salmonella enteritidis*	0–42 days	Improved growth performance, reduced cecal pathogen load at 2 weeks of age	[7]
SDP	0, 2%	Necrotic enteritis	0–10 days	Decreased FCR, increased immune organ weight, enhanced gut integrity, and immune response	[6]
SDP	0, 2%	Mycotoxins		SDP supplementation performance and immune response	[57]

SDP: spray-dried plasma, SDPP: spray-dried porcine plasma, Exp: experiment, BW: body weight, BWG: body weight gain, FI: feed intake, FCR: feed conversion ratio.

Table 4.
Effects of spray-dried plasma on broilers under production or microbial challenges.

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9. Conclusion

SDP has demonstrated significant potential as a feed additive in broiler production, with applications extending beyond nutritional benefits. It has been shown to enhance growth performance, improve immune function, and promote gut health, particularly under conditions of stress or disease. The bioactive components of SDP, including immunoglobulins and growth factors, contribute to immune modulation and attenuation of inflammatory responses while also optimizing nutrient utilization. Although economic factors may limit the widespread adoption of SDP, its proven efficacy, especially under stressful conditions, makes it a viable alternative to antibiotic growth promoters. Consequently, prolonged supplementation of broiler diets at low doses is recommended to enhance productivity and improve the health of broilers.

Conflict of interest

The authors declare no conflict of interest.

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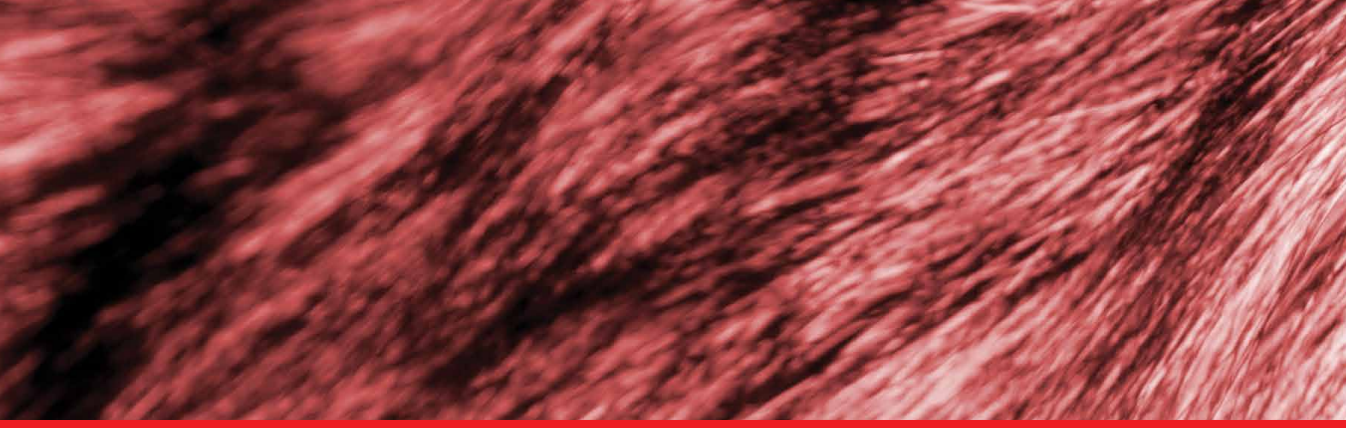

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As the global demand for animal-derived food continues to rise, the feed industry is under increasing pressure to provide nutritional solutions that are high-performance, sustainable and safe. *Animal Feeds and Additives* brings together cutting-edge research and practical insights to address the complex challenges and emerging opportunities shaping modern animal nutrition. This comprehensive volume begins with an in-depth analysis of the current state of the global feed and feed additives industries, as well as their future objectives and strategies. It highlights the key drivers of innovation, ranging from climate change and resource constraints to shifts in consumer expectations and regulatory landscapes. The chapter on using food waste in animal nutrition focuses on sustainability, exploring novel approaches to resource recovery and circular feeding systems. This section demonstrates how rethinking waste can reduce environmental impact while maintaining feed quality and safety. The book also examines the controversial topic of antibiotics in animal feed, presenting a balanced view of their historical benefits and the growing concerns surrounding antimicrobial resistance. This discussion provides context for the industry's ongoing transition towards alternative, health-promoting strategies. Supporting precision nutrition and environmentally responsible livestock production, the chapter on feed additives for ruminants examines how targeted supplements can enhance productivity, reduce methane emissions, and improve overall animal health and welfare. Finally, a review of the effects of spray-dried plasma on broiler chickens sheds light on the role of this promising additive in boosting growth performance, gut health, and immune response. Designed for animal nutritionists, feed manufacturers, researchers and students, *Animal Feeds and Additives* is a valuable guide to the evolving science and strategies behind efficient, ethical and sustainable animal production.

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