Bacterial Vaccines in Poultry

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Contributor: Md. Saiful Islam, Md. Tanvir Rahman

Bacterial vaccines have become a crucial tool in combating antimicrobial resistance (AMR) in poultry. The overuse and misuse of antibiotics in poultry farming have led to the development of AMR, which is a growing public health concern. Bacterial vaccines are alternative methods for controlling bacterial diseases in poultry, reducing the need for antibiotics and improving animal welfare. These vaccines come in different forms including live attenuated, killed, and recombinant vaccines, and they work by stimulating the immune system to produce a specific response to the target bacteria. There are many advantages to using bacterial vaccines in poultry, including reduced use of antibiotics, improved animal welfare, and increased profitability.

Keywords: bacterial vaccines ; antimicrobial resistance ; poultry ; bacterial diseases

1. Introduction

Poultry production is a critical component of the global food industry, providing a low-cost source of protein to millions of people worldwide [1]. However, the poultry industry is facing a significant challenge in the form of antimicrobial resistance (AMR) [2]. AMR refers to the ability of bacteria to resist the effects of antibiotics, and it is driven, in part, by the overuse and misuse of antibiotics in poultry production [3]. The widespread use of antibiotics in poultry production has led to the emergence of antibiotic-resistant bacteria, which can be transmitted to humans through the food chain and cause serious health problems [4]. AMR is a growing public health concern, as it reduces the effectiveness of antibiotics, making it harder to treat bacterial infections [5].

Bacterial vaccines offer a promising strategy for combating AMR in poultry production. Unlike antibiotics, which are broad-spectrum drugs that can target both pathogenic and non-pathogenic bacteria, bacterial vaccines are specific to a particular pathogen and do not have the same impact on the gut microbiome [6]. This means that they are less likely to contribute to the development of AMR, making them a more sustainable alternative to antibiotics. Bacterial vaccines work by stimulating the poultry's immune system to produce a response against specific bacterial pathogens, reducing the need for antibiotics. They offer long-lasting protection against bacterial infections, reducing the need for repeated treatments with antibiotics [7]. Despite the benefits of using bacterial vaccines in poultry, there are also limitations to their use. The use of bacterial vaccines in poultry is regulated by various governmental agencies, and there are economic considerations to be taken into account, including costs and return on investment [8]. Additionally, there is an ongoing debate about the efficacy of bacterial vaccines, and some studies have shown that vaccine efficacy can vary depending on the target bacteria and the specific vaccine used [9][10].

Bacterial vaccines play a critical role in combating the growing problem of AMR in poultry and represent a step towards a more sustainable and responsible approach to poultry farming. With continued research and innovation, bacterial vaccines have the potential to greatly improve the health and welfare of poultry, as well as protect public health by reducing the spread of AMR.

2. Overview of Bacterial Diseases in Poultry

Bacterial diseases in poultry can cause significant morbidity and mortality, leading to economic losses for farmers. Some of the most important bacterial diseases in poultry include the following [11]:

- Salmonellosis: A bacterial infection caused by *Salmonella*, which can lead to severe diarrhea, septicemia, and death in poultry.
- Colibacillosis: A bacterial infection caused by *Escherichia coli*, which can cause severe diarrhea in young chicks and septicemia in adult chickens.

- Avian Mycoplasmosis: A bacterial infection caused by *Mycoplasma gallisepticum*, which affects the respiratory and reproductive systems of poultry and can cause decreased egg production and increased mortality.

- Pasteurellosis: A bacterial infection caused by *Pasteurella multocida*, which affects the respiratory system of poultry and can cause severe pneumonia, septicemia, and death.

- Campylobacteriosis: A bacterial infection caused by *Campylobacter jejuni*, which can cause severe diarrhea, enteritis, and septicemia in poultry.

- *Staphylococcus* infection: A bacterial infection caused by *Staphylococcus aureus*, which can cause skin and wound infections, arthritis, and septicemia in poultry.

- Chlamydiosis: A bacterial infection caused by *Chlamydia psittaci*, which affects the respiratory and reproductive systems of poultry and can cause decreased egg production and increased mortality.

Common bacterial diseases developed in poultry are detailed in **Table 1**.

Table 1. List of bacterial diseases in poultry with their common clinical signs, mode of transmission, common treatments/control vaccines/drugs, and affected bird types [11][12][13][14].

Name of Diseases	Common Clinical Signs	Mode of Transmission	Common Treatment/Control Vaccine/Drugs	Affected Bird Types
Avian salmonellosis	**Depression, poor growth, weakness, severe diarrhea, dehydration, and death.**	**Mainly egg transmission, others include mechanical transmission, carrier birds, contaminated premises, etc.**	**Treatment is mainly a salvage operation. However, antibiotics, e.g., furazolidone, gentamycin sulfate, and sulfa drugs can be used. Vaccines against local strain are used to control the disease.**	**Chickens, turkeys, ducks, pigeons, pheasants, and other game birds.**
Avian colibacillosis	**Ruffled feathers, fever, labored breathing, reduced appetite, poor growth, occasional coughing, rales, diarrhea, and sudden death.**	**Inhalation of the fecal contaminated dust.**	**Early treatment is recommended. Antibiotics such as tetracyclines, sulfas, ampicillin, and streptomycin maybe used to control some *E. coli.***	**All types of poultry.**
Avian Mycoplasmosis	**Coughing, sneezing, respiratory rales, ocular and nasal discharge, decreased feed intake and egg production, increased mortality, poor hatchability, and, primarily in turkeys, swelling of the infraorbital sinus.**	**Vertically within some eggs (transovarian) from infected breeders to progeny, and horizontally via infectious aerosols and through contamination of feed, water, and the environment, and by human activity on fomites (shoes, equipment, etc.).**	**Can be treated with antibiotics to alleviate clinical symptoms. Tylosin, tilmicosin, and tiamulin are useful to reduce the mycoplasma load in the flock. However, antibiotic therapy cannot completely eliminate mycoplasma from the flock. Moreover, vaccines against local strain are used to control the disease.**	**Chickens and turkeys.**
Pasteurellosis	**Stupor, loss of appetite, rapid weight loss, lameness resulting from joint infection, swollen wattles, difficult breathing, watery yellowish or green diarrhea, cyanosis or darkening of the head and wattles, and sudden death.**	**Ingestion, mechanically by arthropod vectors or by inhalation.**	**Treatment is not practical, but when individual treatment is applicable, chlortetracycline, oxytetracycline, and sulfaquinoxaline can be used. Vaccines against a local strain are used to control the disease.**	**Chickens, turkeys, pheasants, pigeons, waterfowl, sparrows, and other free-flying birds.**
Necrotic Enteritis	**Severe depression, ruffled feathers, diarrhea, and sudden increased mortality.**	**Oral contact with the droppings from infected birds.**	**Bacitracin, penicillin, and lincomycin most often used.**	**Mainly broiler chickens. Layers and turkeys can also be affected.**

Name of Diseases	Common Clinical Signs	Mode of Transmission	Common Treatment/Control Vaccine/Drugs	Affected Bird Types
Campylobacteriosis	**Decreased egg production; death can occur rapidly.**	**Through a contaminated water source or through contact with feces.**	**Can be treated with antibiotics, e.g., azithromycin. Bacteriocin OR-7 treatment is also useful.**	**Broilers, layers, turkeys, ducks, and geese.**
***Staphylococcus* infection**	**Affected chicks usually appear drowsy or droopy with the down being "puffed up". Diarrhea sometimes occurs. Mortality usually begins within 24 hours and peaks by 5-7 days.**	**Transmitted from unsanitary equipment in the hatchery to newly hatched birds having unhealed navels.**	**Staphylococcosis can be successfully treated with antibiotics, e.g., penicillin, erythromycin, lincomycin, and spectinomycin.**	**Chickens.**
Infectious Coryza	**Edematous swelling of the face around the eyes and wattles, nasal discharge and swollen sinuses.**	**By direct contact, airborne infection by dust or respiratory discharge droplets and drinking water contaminated by infective nasal exudate**	**A number of drugs (e.g., Sulfadimethoxine or sulfathiazole) are effective for treating the symptoms of the disease although the disease is never completely eliminated.**	**Chickens.**
Chlamydiosis	**Anorexia, ruffled feathers, apathy, drop in egg production, diarrhea, weight loss, ocular discharge, fever, and respiratory distress.**	**By the fecal-oral route or by inhalation.**	**Tetracyclines (chlortetracycline, oxytetracycline, doxycycline) are the antibiotics of choice.**	**Turkeys, ducks, and chickens.**

Bacterial diseases in poultry have significant impacts on the poultry industry. The diseases can cause high mortality rates in poultry, decreased egg production, and reduced quality of meat and eggs. These losses can result in significant financial losses for poultry farmers and the poultry industry as a whole [15]. Additionally, bacterial diseases in poultry can lead to increased use of antibiotics, contributing to the development of antibiotic resistance.

Controlling bacterial diseases in poultry is crucial for the health and productivity of poultry and for the profitability of poultry production. Effective control measures can include biosecurity measures, such as good sanitation practices, controlling the movement of poultry, and preventing the introduction of infected chickens into a flock. Additionally, vaccination programs can play an important role in controlling bacterial diseases in poultry, providing an effective and cost-efficient way to prevent or reduce the impact of bacterial diseases in poultry.

3. Antibiotics Contribute to Antimicrobial Resistance

Antibiotics are powerful medicines that have revolutionized modern medicine by providing a way to treat bacterial infections that were once life-threatening. However, their widespread use has led to the development of antibiotic resistance, which is one of the most significant threats to global public health today [16][17]. The following are some ways in which antibiotics contribute to the development of antimicrobial resistance [18][19][20][21][22]:

- Overuse and misuse of antibiotics: Overuse and misuse of antibiotics are the primary causes of antibiotic resistance. Antibiotics are often prescribed for viral infections that they cannot cure, leading to unnecessary exposure to antibiotics, and making it easier for bacteria to develop resistance. Moreover, people often stop taking antibiotics once they feel better, not realizing that the bacteria may still be present, leading to incomplete treatment and the development of resistance.

- Selection pressure: Antibiotics exert strong selection pressure on bacteria, killing off the susceptible ones and allowing the resistant ones to survive and multiply. The resistant bacteria then go on to spread their resistance genes to other bacteria through horizontal gene transfer, including plasmids, transposons, and integrons. This horizontal transfer of resistance genes can occur within and between different species, making it harder to control the spread of resistance.

- Antibiotic residues in the environment: Antibiotics and their metabolites can persist in the environment for a long time after they are used, even at low concentrations. This can lead to the selection of resistant bacteria in the environment, which can then spread to humans and animals. Antibiotic residues in water bodies can also contribute to the spread of resistance, as they can lead to the selection of resistant bacteria in aquatic environments.

- Agricultural use of antibiotics: Antibiotics are widely used in agriculture, both to treat and prevent infections in animals and as growth promoters. This can lead to the selection of resistant bacteria in animals, which can then spread to humans through the food chain or the environment. Moreover, the use of antibiotics in agriculture contributes to the spread of resistance by releasing antibiotic residues into the environment.

- Lack of new antibiotics: The development of new antibiotics has slowed down in recent years, partly due to the high cost and time required for the development. This means that the antibiotics researchers have now are becoming less effective against resistant bacteria, which can lead to the further spread of resistance.

4. Antimicrobial Resistance in Poultry

AMR refers to the ability of microorganisms, including bacteria, viruses, fungi, and parasites, to resist the effects of antimicrobial drugs that were previously effective in treating infections caused by these microorganisms. AMR is a growing global public health threat and a major concern in the poultry industry [23], as poultry are often treated with antibiotics to prevent and control bacterial diseases. Moreover, antimicrobial-resistant bacteria in poultry can pose a risk to human health through the consumption of contaminated poultry products [24].

There are several mechanisms by which bacteria can develop resistance to antibiotics [25], including the following:

- Mutations: Bacteria can undergo genetic mutations that alter their structure and make them resistant to antibiotics.

- Horizontal gene transfer: This occurs when bacteria transfer genes that confer resistance to antibiotics to other bacteria through mechanisms such as conjugation, transduction, and transformation.

- Antibiotic pressure: The overuse and misuse of antibiotics can select bacteria that are resistant to these drugs.

The development of AMR in poultry has significant impacts on the poultry and poultry industry [26], including the following (**Figure 1**):

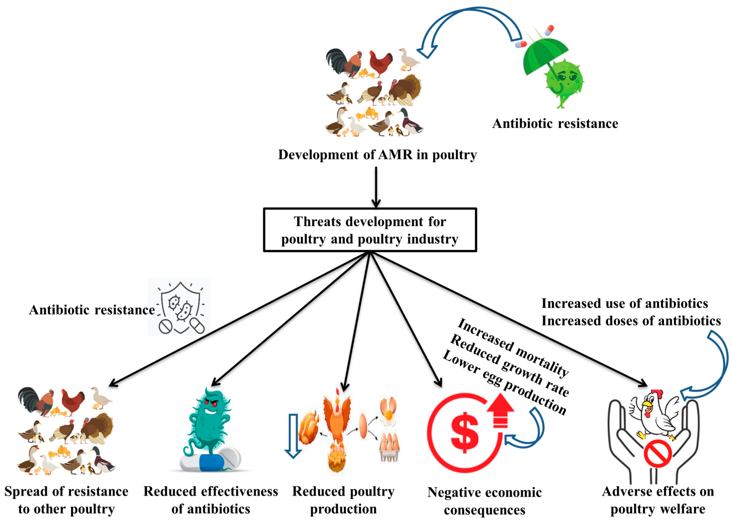

Figure 1. Possible threats of antimicrobial resistance on poultry and poultry production.

- Spread of resistance: Antibiotic-resistant bacteria can spread from poultry to poultry through direct contact or the environment. This can contribute to the spread of resistance and make it more challenging to control bacterial infections in poultry. Moreover, resistance genes can be transferred from bacteria in poultry to bacteria in other poultry through horizontal gene transfer, leading to the further spread of resistance.

- Reduced efficacy of antibiotics: Antibiotic-resistant bacteria are more difficult to treat and can lead to prolonged illness and increased mortality in poultry.

- Impact on animal welfare: The use of antibiotics in poultry can contribute to the development of antibiotic-resistant bacteria, which can lead to the increased use of antibiotics and the use of higher doses, leading to the potential for adverse effects on animal welfare.

- Increased costs: The treatment of antibiotic-resistant infections can be more expensive and time-consuming than the treatment of infections caused by susceptible bacteria.

- Reduced productivity: Antimicrobial-resistant infections can reduce the health and productivity of poultry flocks, leading to decreased egg production and reduced meat quality.

5. Overview of the History of Bacterial Vaccines in Poultry

Bacterial vaccines have been used in poultry production for several decades [27]. Since then, the use of bacterial vaccines in poultry has grown, and they are now widely recognized as an important tool for controlling bacterial infections in poultry. The early history of bacterial vaccines in poultry was marked by a focus on the development of killed or inactivated bacterial vaccines. These vaccines were made by growing a specific pathogen in the laboratory and then killing it with chemicals or heat to prevent it from causing disease. The killed bacteria were then used to produce the vaccine, which was administered to poultry to stimulate the production of antibodies that would protect against future infections with the same pathogen. Despite the initial success of these vaccines, they were limited by their inability to provide long-lasting protection against bacterial infections. The effectiveness of killed vaccines would decrease over time, requiring frequent booster shots to maintain protection. This led to a shift in focus towards the development of live, attenuated vaccines, which could provide longer-lasting protection against bacterial infections. Another important development in the history of bacterial vaccines in poultry was the introduction of recombinant vaccines. Recombinant vaccines are made by using genetic engineering techniques to produce a vaccine that contains a specific, targeted piece of the pathogen’s genetic material. These vaccines are highly specific, allowing them to target only the pathogen of concern without affecting other bacteria in the gut microbiome. This makes them a more sustainable alternative to antibiotics, as they do not contribute to the development of antibiotic-resistant bacteria. In recent years, there has been a growing interest in the development of bacteriophage-based vaccines. Bacteriophages are viruses that specifically target bacteria, and they have been shown to be highly effective at controlling bacterial infections in poultry. Bacteriophage-based vaccines work by introducing bacteriophages into the poultry, which then infect and destroy specific bacterial pathogens, reducing the need for antibiotics [7][28][29][30][31].

6. Properties of a Comparative Study of Different Bacterial Vaccines for Poultry

A comparative study of different bacterial vaccines for poultry involves evaluating and comparing the efficacy, safety, and cost-effectiveness of different bacterial vaccines available for poultry. This type of study is important because it helps to determine the best vaccine for a particular use based on the specific needs of the poultry industry.

There are several factors that can be considered in a comparative study of bacterial vaccines [32][33][34][35][36], including the following:

- Efficacy: This refers to the ability of the vaccine to effectively prevent or control the target bacterial infection. The efficacy of a vaccine can be determined through field trials, laboratory experiments, and/or observational studies.

- Safety: The safety of a vaccine is determined by evaluating the potential adverse effects associated with its use, such as local or systemic reactions, toxicity, and interference with other vaccines.

- Cost-effectiveness: The cost-effectiveness of a vaccine is determined by evaluating the cost of the vaccine in relation to the benefits it provides, such as reducing the need for antibiotics, improving productivity, and reducing the risk of AMR.

- Administration: The ease of administration of a vaccine can also be considered, including the route of administration, dosage, and storage requirements.

- Durability: The durability of a vaccine refers to its ability to provide long-lasting protection against the target bacterial infection.

- Spectrum of activity: The spectrum of activity of a vaccine refers to the range of bacterial strains that the vaccine can protect against.

By evaluating these factors, a comparative study of different bacterial vaccines for poultry can provide valuable information on the relative strengths and weaknesses of different vaccines and help to determine the best vaccine for a particular use. It is important to note that the results of a comparative study may vary depending on the specific circumstances and conditions of the poultry industry, such as the type of poultry, the prevalence of bacterial infections, and the specific needs of the industry. As such, it is important to conduct ongoing studies to evaluate and compare the performance of different vaccines in different circumstances. A comparative study of different bacterial vaccines for poultry is an important tool for evaluating the efficacy, safety, and cost-effectiveness of different vaccines and for determining the best vaccine for a particular use. Ongoing studies are necessary to ensure that the best vaccine is selected for the specific needs of the poultry industry. Top of Form.

7. Potential Mechanisms of Action of Bacterial Vaccines in Poultry

Bacterial vaccines work by stimulating the poultry's immune system to produce a response against specific pathogens. This provides protection against future infections with the same pathogen, reducing the need for antibiotics. There are several mechanisms of action of bacterial vaccines, each of which provides a different approach to controlling bacterial infections in poultry [37][38][39][40][41]:

- The first mechanism of action is the stimulation of the immune response. When a bird is vaccinated, its immune system produces a response against the vaccine, which includes the production of antibodies. These antibodies are specific to the pathogen targeted by the vaccine, and they provide protection against future infections with the same pathogen. This is known as active immunity, and it provides long-lasting protection against bacterial infections.

- The second mechanism of action is the competition for nutrients and attachment sites. Some bacterial vaccines work by introducing a benign, or "competitor" bacteria into the poultry's gut. This competitor bacteria competes with pathogenic bacteria for nutrients and attachment sites in the gut, reducing their ability to colonize and cause disease. This is known as competitive exclusion, and it is a highly effective approach to controlling bacterial infections in poultry.

- The third mechanism of action of bacterial vaccine is a cell-mediated immune response. Bacterial vaccines also stimulate the production of T-cells, which are a type of white blood cell that can directly attack infected cells and help activate other cells in the immune system. T-cells can recognize specific bacterial antigens and release cytokines (small proteins that regulate the immune response) to activate other cells in the immune system.

- Another mechanism of action of bacterial vaccines is the stimulation of phagocytosis. Phagocytosis is the process by which immune cells called phagocytes engulf and destroy bacteria. Bacterial vaccines stimulate the production of phagocytes, such as macrophages and neutrophils, which can recognize and engulf bacteria.

Each of these mechanisms of action provides a different approach to controlling bacterial infections in poultry, and they have been shown to be highly effective in reducing the need for antibiotics. This is particularly important in the context of AMR, as the overuse of antibiotics in poultry production has contributed to the development of antibiotic-resistant bacteria.

8. Different Types of Bacterial Vaccines Used in Poultry and Their Efficacy

Bacterial vaccines are used to provide protection against specific bacterial infections in poultry. There are several different types of bacterial vaccines used in poultry. Researchers will discuss the different types of bacterial vaccines used in poultry [7] as follows:

- Inactivated bacterial vaccines: Inactivated bacterial vaccines are made by killing the bacteria and then purifying and inactivating the vaccine. These vaccines stimulate the immune system to produce a response against the specific pathogen, providing long-lasting protection against future infections. Examples of inactivated bacterial vaccines used in poultry include vaccines against *Salmonella*, *Campylobacter*, and *E. coli*.

- Live attenuated bacterial vaccines: Live attenuated bacterial vaccines are made by attenuating or weakening the bacteria, so they are no longer harmful but still able to stimulate an immune response. These vaccines can provide long-lasting protection against future infections with the same pathogen. Examples of live attenuated bacterial vaccines used in poultry include vaccines against Newcastle disease, infectious bronchitis, and fowl pox.

- Subunit bacterial vaccines: Subunit bacterial vaccines are made by purifying and isolating specific proteins or antigens from the bacteria and then using these antigens to stimulate an immune response. These vaccines can be highly effective but may require multiple doses to provide long-lasting protection against future infections. Examples of subunit bacterial vaccines used in poultry include vaccines against *Salmonella*, *Campylobacter*, and *E. coli*.

- Recombinant bacterial vaccines: Recombinant bacterial vaccines are made by using genetic engineering techniques to introduce specific antigens into a harmless vector, such as a bacterium or yeast. These vaccines can provide highly effective protection against specific bacterial pathogens and may only require a single dose to provide long-lasting protection. Examples of recombinant bacterial vaccines used in poultry include vaccines against *Salmonella* and *Campylobacter*.

The efficacy of bacterial vaccines in poultry can vary depending on several factors, including the type of vaccine, the specific pathogen being targeted, the age and health status of the poultry, and the management practices used in the poultry production system [7]. In general, bacterial vaccines have been shown to be highly effective in controlling bacterial infections in poultry, reducing the need for antibiotics, and improving animal performance. However, it is important to note that bacterial vaccines are not a panacea and cannot provide protection against all bacterial pathogens. In addition, the efficacy of bacterial vaccines can be reduced by factors such as poor storage and handling, incorrect administration, or the presence of other diseases or stressors in poultry.

9. Commercially Available Vaccines for Poultry Bacterial Diseases

Commercially available bacterial vaccines for poultry are widely used to control and prevent bacterial infections in poultry farms. These vaccines are generally produced from killed or attenuated bacterial cells or their toxins, and they stimulate the bird's immune system to produce an immune response that can protect against bacterial infections. Below are some commonly used bacterial vaccines for poultry [27][42]:

- *Salmonella* vaccine: This vaccine is used to prevent *Salmonella* infections in poultry. It is composed of killed bacteria or a live attenuated strain that has been modified to reduce its virulence. Vaccinating birds against a particular serovar that is specific to their host, such as *Salmonella gallinarum*, results in the development of a robust and targeted immune response. The vaccine can be administered through drinking water or injection. The largest selection of available vaccines is designed to target serovar Enteritidis and Typhimurium. These vaccines are typically given through subcutaneous injection when birds are between 10 to 14 weeks old, with two separate doses administered 4 to 6 weeks apart.

- Infectious coryza vaccine: This vaccine is used to protect against infectious coryza (caused by *Haemophilus paragallinarum* or *Avibacterium paragallinarum*), a bacterial respiratory disease that affects poultry. The vaccine is typically produced from killed or inactivated bacteria. In the United States and other nations, there are commercial bacterins that typically consist of all serovars of the bacterium. Certain vaccines made by large manufacturers are marketed globally and contain the most common bacterial strains. Nonetheless, there are worries that such vaccines may not protect against locally prevalent variants. These types of vaccines are normally administered through drinking water or injection.

- Avian *E. coli* vaccine: This vaccine is used to prevent *E. coli* infections in poultry. It is commonly produced from live attenuated bacteria and administered through drinking water or injection. However, currently, in the United States, there exists only a live attenuated vaccine option. This vaccine features a mutant strain with an *aroA* deletion. The administration of antibiotics is not allowed when using this vaccine.

- *Pasteurella multocida* vaccine: *Pasteurella multocida* vaccines are available in different forms, including bacterins combined with aluminum hydroxide or oil emulsions, or with weakened live organisms. Multivalent *P. multocida* vaccines usually have serotypes 1, 3, and 4, which are the most common. Inactivated vaccines are typically administered through injection, while attenuated live vaccines (using M9 or PM-1 strains) can be given through the wing web or drinking water. It takes about two weeks for immunity to develop after vaccination.

- Avian mycoplasma vaccine: This vaccine is used to prevent *Mycoplasma gallisepticum* and *Mycoplasma synoviae* infections in poultry. The vaccine is typically produced from killed or attenuated bacteria. Live MG vaccines are available in several types, such as the mild F strain, the safer avirulent ts-11 or 6/85 strains, etc. The F strain can be given through intranasal or eye drop methods, while the ts-11 strain is administered through eye drops and the 6/85 strain through fine spray. The use of these attenuated vaccines is considered controlled exposure, which means they cause only mild infection at an age when it is less damaging. The vaccination of pullets is generally employed between 12 to 16 weeks of age, and one dose is enough to make them permanent carriers. Moreover, a live MS vaccine with the MS-H strain is given by eye drop.

In addition to these vaccines, there are other commercially available bacterial vaccines for poultry, such as those used to prevent *Clostridium perfringens* infections. The summary of commercially available bacterial vaccines against various common bacterial diseases are documented in **Table 2**.

Table 2. List of commercially available bacterial vaccines against different common bacterial diseases in poultry production [27][43][44][45][46].

Name of Commercial Bacterial Vaccines	Vaccine Types	Name of Manufacturers, Country	Pathogens or Species	Name of Bacterial Diseases
AviPro®MEGAN®VAC 1	Live, attenuated vaccine Δ*cya*/Δ*crp* mutation	Elanco Animal Health, USA	*Salmonella* Typhimurium, *Salmonella* Enteritidis, and *Salmonella* Heidelberg	Avian salmonellosis
Vaxsafe®ST	Live, attenuated vaccine Δ*aroA* mutation	Bioproperties Pty Ltd., Australia	*Salmonella* Typhimurium	Avian salmonellosis
AviPro®*Salmonella* Vac E	Live, attenuated vaccine (Sm24/Rif12/Ssq strain)	Elanco Animal Health, USA	*Salmonella* Enteritidis	Avian salmonellosis
AviPro®Megan®Egg	Live, attenuated vaccine Δ*aroA* mutation	Elanco Animal Health, USA	*Salmonella* Enteritidis, *Salmonella* Typhimurium	Avian salmonellosis
Poulvac®ST	Live, attenuated vaccine Δ*aroA* mutation	Zoetis, USA	*Salmonella* Typhimurium	Avian salmonellosis
AviPro 109 SE4 Conc	Inactivated vaccine	Lohmann Animal Health, Germany	*Salmonella* Enteritidis	Avian salmonellosis
Gallivac®SE	Live, attenuated vaccine Δ*aroA* mutation	Merial Select, Italy	*Salmonella* Enteritidis	Avian salmonellosis
SALMUNE®	Live, attenuated vaccine	Ceva Animal Health, USA	*Salmonella* Typhimurium	Avian salmonellosis
Poulvac®*E. coli*	Live, attenuated vaccine Δ*aroA* mutation, O78 serotype	Zoetis, USA	*Escherichia coli*	Avian colibacillosis
Avipro 101 Coryza Gold	Inactivated (serotype A,B,C)	Lohmann Animal Health, Cuxhaven, Germany	*Haemophilus paragallinarum*	Infectious coryza
Coripravac-O	Killed [serotype A (strain 1753) + B (strain 1755) + C (strain 1756)	Hipra, Spain	*Avibacterium paragallinarum*	Infectious coryza
M-NINEVAX®-C	Live vaccine with mild avirulent M-9 strain	Merck, USA	*Pasteurella multocida*	Fowl cholera
Gallimune Cholera/Bio Chlolera	Inactivated (serotypes 1, 3 and 4.)	Merial Select, Italy	*Pasteurella multocida*	Fowl cholera
Multimune K5	Killed (serotypes 1, 3 & 4 + serotypes 3&4)	Biomune, USA	*Pasteurella multocida*	Fowl cholera
PM-ONEVAX®-C	Live vaccine with mild avirulent PM-1 strain	Merck, USA	*Pasteurella multocida*	Fowl cholera
MyVAC DP	Killed vaccine (serotype 1)	MVP Sdn. Bhd., Malaysia	*Pasteurella multocida*	Duck Pasteurellosis
MG TS-11	Live attenuated vaccine (TS-11 strain)	Merial Select, Italy	*Mycoplasma gallisepticum*	Avian mycoplasmosis
Gallimune MG/BioMyco/MG Vax	Killed vaccine (S6 strain)	Merial Select, Italy	*Mycoplasma gallisepticum*	Avian mycoplasmosis
AviPro®MG-F	Live attenuated vaccine (F strain)	Elanco Animal Health, USA	*Mycoplasma gallisepticum*	Avian mycoplasmosis
MG BacterinMS Bacterin	Bacterin (F strain)	Zoetis, USA	*Mycoplasma gallisepticum*, *Mycoplasma synoviae*	Avian mycoplasmosis
MYCOVAC-L®	Live vaccine (Intervet 6/85 strain)	Merck, USA	*Mycoplasma gallisepticum*	Avian mycoplasmosis

Name of Commercial Bacterial Vaccines	Vaccine Types	Name of Manufacturers, Country	Pathogens or Species	Name of Bacterial Diseases
Myc-vac	**Killed (NEV40 & NEV45 strain)**	**Fatro S.p.A, Italy**	***Mycoplasma gallisepticum***	**Avian mycoplasmosis**
Poulvac®MycoF	**Live attenuated vaccine (F strain)**	**Zoetis, USA**	***Mycoplasma gallisepticum***	**Avian mycoplasmosis**

10. Advantages and Disadvantages of Bacterial Vaccines in Poultry

Bacterial vaccines have become an important tool for controlling bacterial infections in poultry, and for reducing the need for antibiotics. However, like all interventions, bacterial vaccines have both advantages and disadvantages that need to be considered when deciding whether to use them in a poultry production system.

Potential advantages of bacterial vaccines in poultry are listed in the following [47][48][49][50][51]:

- Reduced need for antibiotics: The primary advantage of bacterial vaccines is that they reduce the need for antibiotics. By stimulating the poultry's immune system to produce a response against specific pathogens, bacterial vaccines provide protection against future infections with the same pathogen, reducing the need for antibiotics. This is particularly important in the context of AMR, as the overuse of antibiotics in poultry production has contributed to the development of antibiotic-resistant bacteria.

- Increased immunity: Bacterial vaccines can also provide increased immunity against specific bacterial pathogens. By stimulating the poultry's immune system to produce a response against the pathogen, bacterial vaccines provide long-lasting protection against future infections with the same pathogen. This can improve the health and welfare of the poultry, as well as reduce the need for antibiotics.

- Improved animal performance: Improved immunity against bacterial infections can also result in improved animal performance. Poultry that are protected against bacterial infections are less likely to experience disease, reducing the need for antibiotics and improving overall health. This can result in improved feed conversion, weight gain, and egg production.

- Reduced spread of antibiotic-resistant bacteria: Bacterial vaccines can also help to reduce the spread of antibiotic-resistant bacteria. By controlling bacterial infections in poultry, bacterial vaccines reduce the need for antibiotics, and, in turn, reduce the exposure of bacteria to antibiotics. This reduces the selection pressure for antibiotic-resistant bacteria, reducing their spread to other poultry and to the environment.

- Reduced risk of transmission to humans: Bacterial vaccines can also help to reduce the risk of transmission of bacterial infections from poultry to humans. By controlling bacterial infections in poultry, bacterial vaccines reduce the risk of bacterial pathogens being spread to humans through the food supply, reducing the risk of human infections.

Potential disadvantages of bacterial vaccines in poultry are listed in the following [8][30][52][53][54]:

- Cost: One of the main disadvantages of bacterial vaccines is their cost. Bacterial vaccines can be more expensive than antibiotics, particularly in large-scale poultry production systems. This can make them less accessible to some producers, particularly in developing countries.

- Ineffectiveness against some pathogens: Bacterial vaccines may not be effective against all bacterial pathogens, and some may be better suited to certain types of infections than others. This means that producers need to carefully select the most appropriate bacterial vaccine for their needs.

- Time to efficacy: Bacterial vaccines may take several weeks to become effective, during which time the poultry may still be susceptible to infection. This can result in a period of increased risk and may require the use of antibiotics in the meantime.

- Limited availability: Bacterial vaccines may not be widely available in all countries, particularly in developing countries. This can limit their use in some regions, and producers may need to import vaccines from other countries, which can be costly and logistically challenging.

11. The Role of Bacterial Vaccines in Reducing Antimicrobial Resistance in Poultry

The use of antibiotics in poultry production has been a topic of concern for several decades due to the growing problem of AMR [55]. Bacterial vaccines have emerged as a promising alternative to the use of antibiotics in poultry production. Bacterial vaccines work by stimulating the immune system of poultry to produce a response against specific bacterial pathogens, providing long-lasting protection against future infections. By reducing the incidence of bacterial infections in poultry, bacterial vaccines can reduce the need for antibiotics, helping to slow the development of AMR (**Figure 2**).

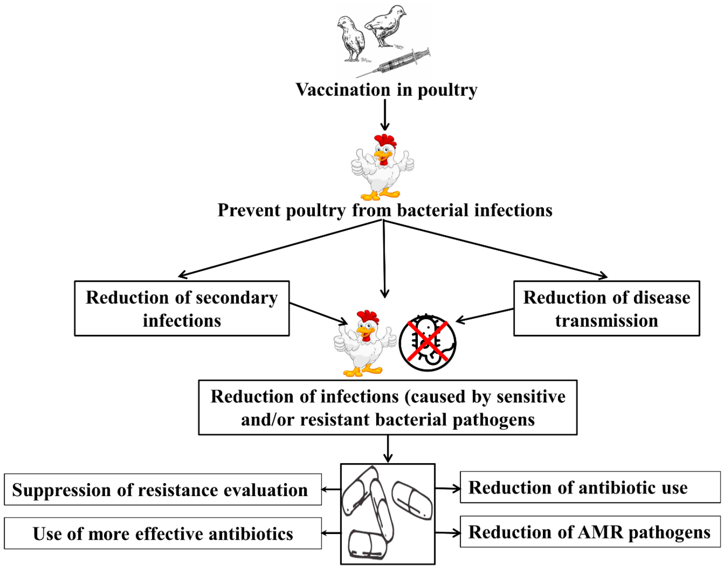

Figure 2. The role of bacterial vaccination in reducing the use of antibiotics and the occurrence of antimicrobial resistance in poultry.

The role of bacterial vaccines in reducing the use of antibiotics in poultry can be seen in several different ways [9][48][56][57][58][59][60]: (a) Bacterial vaccines can help to prevent bacterial infections in the first place. By stimulating the immune system of poultry, bacterial vaccines can provide long-lasting protection against specific bacterial pathogens, reducing the need for antibiotics to treat bacterial infections. This can lead to a significant reduction in the use of antibiotics, helping to slow the development of AMR. (b) Bacterial vaccines can help to reduce the severity of bacterial infections. By stimulating the immune system of poultry, bacterial vaccines can help to reduce the severity of bacterial infections, reducing the need for antibiotics to treat the infections. This is especially important in the context of AMR, as reducing the severity of bacterial infections can reduce the need for antibiotics and help to slow the development of resistance. (c) Bacterial vaccines can help to improve the overall health and performance of poultry. By reducing the incidence and severity of bacterial infections, bacterial vaccines can help to improve the overall health and performance of poultry, reducing the need for antibiotics to treat bacterial infections and improving the efficiency of poultry production. This can lead to improved economic outcomes for poultry producers, as well as better health outcomes for the poultry themselves.

12. Conclusions and Recommendations

Bacterial vaccines have shown promising results in combating AMR in poultry. Bacterial vaccines provide a specific and long-lasting immunity against targeted bacterial pathogens and have the potential to reduce the spread of AMR. However, the development and implementation of bacterial vaccines are not without challenges. Further research is needed to fully understand the mechanisms of action of bacterial vaccines, their relative efficacy in comparison to other alternative strategies, and their potential impact on the poultry industry.

In order to fully realize the potential of bacterial vaccines in combating AMR in poultry, it is recommended that the following research and implementation initiatives be pursued:

- Development of new and improved bacterial vaccines: Research should be conducted to develop new and improved bacterial vaccines that are specific to the targeted bacterial pathogens and that offer long-lasting immunity.

- Efficacy studies: Further research is needed to fully understand the efficacy of bacterial vaccines in controlling AMR in poultry. This includes large-scale trials to determine the effectiveness of bacterial vaccines in reducing the spread of AMR and the impact of bacterial vaccines on the poultry industry.

- Regulatory support: Regulators should provide support for the development and implementation of bacterial vaccines in poultry. This includes the establishment of a regulatory framework for the development and commercialization of bacterial vaccines and the provision of technical assistance for the implementation of bacterial vaccines in the field.

- Industry support: The poultry industry should provide support for the development and implementation of bacterial vaccines. This includes the provision of resources for research and development, the promotion of the use of bacterial vaccines in poultry production, and the establishment of incentives for the use of bacterial vaccines in the field.

- Education and outreach: Education and outreach efforts should be conducted to raise awareness of the importance of bacterial vaccines in combating AMR in poultry. This includes the development of educational materials for producers and consumers and the engagement of stakeholders in the poultry industry to promote the use of bacterial vaccines.

Overall, bacterial vaccines have the potential to play a significant role in combating AMR in poultry. However, it will require a concerted effort from researchers, regulators, the poultry industry, and the public to fully realize this potential.

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