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Original article

BACTERIOCINS FOR AGRICULTURE AND AQUACULTURE

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Abstract

Background. The aggravation of the problem of antimicrobial resistance caused by the irrational use of antibiotics in agriculture and aquaculture necessitates the search for sustainable and safe alternatives. Bacteriocins are ribosomally synthesized antimicrobial peptides of bacterial origin. A class of natural compounds for combating resistant pathogens with minimal environmental impact. This review explores the complex potential of using bacteriocins as an alternative to antibiotics. A detailed analysis of the structural diversity, classification approaches, and established mechanisms of antimicrobial action was carried out, including disruption of cell membrane integrity, inhibition of cell wall synthesis, and inhibition of nucleic acid and protein production. Key bacteriocin-producing genera (*Bacillus, Streptomyces*, and *Pseudomonas*) and their biologically active metabolites have been identified. The analysis of bacteriocins' use in agriculture, in particular their role as agents of biocontrol of phytopathogens, plant growth promoters, as well as means of improving the health and productivity of farm animals and birds. Their potential in aquaculture for disease control (directed against pathogens such as *Vibrio* spp., *Aeromonas* spp., *Yersinia ruckeri*), water quality improvement, and feed conservation is considered, which helps reduce dependence on the preventive use of antibiotics. Despite significant achievements, challenges remain related to in vivo efficacy assessment, development of delivery systems, the possibility of resistance development, and regulatory aspects. Addressing these issues is a key condition for realizing the potential of bacteriocins as environmentally sound tools for ensuring food security and sustainable development of terrestrial and aquaculture systems.

Purpose. The aim of this review is to comprehensively analyze the potential of bacteriocins as a sustainable alternative to antibiotics in agriculture and aquaculture. This involves summarizing current knowledge on their structural diversity, classification, mechanisms of antimicrobial action, key producer genera, and practical applications in crop production, livestock farming, and aquaculture disease management.

Materials and methods. This study is a descriptive review. The material for the analysis was composed of contemporary scientific literature sourced from databases such as PubMed, Scopus, and Google Scholar. The methodology included a systematic search, selection, and critical analysis of publications focusing on bacteriocin production, classification, mechanisms of action, and their applications in terrestrial and aquatic agricultural systems. The review synthesizes data from in vitro and in vivo studies to present a holistic overview of the field.

Results. The analysis reveals the significant structural and functional diversity of bacteriocins, which can be classified into several classes (e.g., lantibiotics, unmodified peptides) based on genetic and structural criteria. Their antimicrobial mechanisms are multifaceted, primarily involving pore formation in target cell membranes, inhibition of cell wall synthesis (e.g., via lipid II binding), and disruption of nucleic acid and protein synthesis. Key soil-derived genera, including *Bacillus*, *Streptomyces*, and *Pseudomonas*, are prolific producers of diverse bacteriocins with activity against major plant, animal, and aquatic pathogens (e.g., *Listeria*, MRSA, *Aeromonas*, *and Vibrio*). In agriculture, bacteriocins demonstrate potential as biocontrol agents against phytopathogens and as plant growth promoters. In aquaculture, their applications span disease control, water quality improvement, feed preservation, and use as probiotic supplements, contributing to enhanced animal health and reduced reliance on prophylactic antibiotics.

Conclusion. Bacteriocins emerge as a highly promising and environmentally sound tool for enhancing the sustainability and productivity of both terrestrial and aquatic agricultural systems. Their targeted activity against key pathogens, role in biocontrol and growth stimulation, and ability to preserve product quality with minimal impact on beneficial microbiota underscore their potential. However, translating this potential into practical, scalable solutions necessitates addressing several challenges. Future efforts must focus on robust in vivo efficacy testing, the development of effective delivery systems, understanding the risks of resistance development, and navigating the regulatory landscape. Interdisciplinary research is crucial to bridge the gap between laboratory findings and field application.

Keywords: bacteriocins; sustainable agriculture; aquaculture disease management; fish pathogens; probiotics; soil bacteria

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Научная статья

БАКТЕРИОЦИНЫ ДЛЯ СЕЛЬСКОГО ХОЗЯЙСТВА И АКВАКУЛЬТУРЫ

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Аннотация

Обоснование. Обострение проблемы антимикробной резистентности, вызванной нерациональным использованием антибиотиков в сельском хозяйстве и аквакультуре, обуславливает необходимость поиска устойчивых и безопасных альтернатив. Бактериоцины представляют собой рибосомно синтезируемые антимикробные пептиды бактериального происхождения – класс природных соединений для борьбы с резистентными патогенами, обладающий минимальным воздействием на окружающую среду. В данном обзоре исследуется комплексный потенциал применения бактериоцинов в качестве альтернативы антибиотикам. Проведен детальный анализ структурного разнообразия, подходов к классификации и установленных механизмов антимикробного действия, включая нарушение целостности клеточной мембраны, ингибирование синтеза клеточной стенки, а также подавление синтеза нуклеиновых кислот и белков. Определены ключевые продуцирующие бактериоцины роды (*Bacillus, Streptomyces и Pseudomonas*) и их биологически активные метаболиты. Проанализировано применение бактериоцинов в сельском хозяйстве, в частности их роль в качестве агентов биоконтроля фитопатогенов, стимуляторов роста растений, а также средств улучшения здоровья и продуктивности сельскохозяйственных животных и птиц. Рассмотрен их потенциал в аквакультуре для контроля заболеваний (направленных против таких патогенов, как *Vibrio* spp., *Aeromonas* spp., *Yersinia* ruckeri), улучшения качества воды и консервации кормов, что способствует сокращению зависимости от превентивного использования антибиотиков. Несмотря на значительные достижения, сохраняются проблемы, связанные с оценкой эффективности in vivo, разработкой систем доставки, возможностью развития резистентности и регуляторными аспектами. Решение этих вопросов является ключевым условием для реализации потенциала бактериоцинов в качестве экологически безопасных инструментов обеспечения продовольственной безопасности и устойчивого развития наземных и аквакультурных систем.

Цель. Провести комплексный анализ потенциала применения бактериоцинов в качестве альтернативы антибиотикам в сельском хозяйстве и аквакультуре, обобщив данные об их классификации, механизмах действия, основных продуцентах и направлениях использования.

Материалы и методы. Проведен обзор и анализ современных научных литературных источников, посвященных бактериоцинам, их продуцентам (включая роды *Bacillus, Streptomyces, Pseudomonas*), механизмам антимикробного действия и практическому применению в агросекторе и аквакультуре.

Результаты. Систематизированы данные о структурном разнообразии и классификации бактериоцинов. Подробно описаны установленные механизмы их антимикробного действия, включая нарушение целостности клеточной мембраны, ингибирование синтеза клеточной стенки, нуклеиновых кислот и белков. Выявлены ключевые роды бактерий-продуцентов и охарактеризованы их биологически активные метаболиты. Проанализированы возможности применения бактериоцинов в растениеводстве в качестве агентов биоконтроля фитопатогенов и стимуляторов роста растений, а также в животноводстве и птицеводстве для улучшения здоровья и продуктивности. Рассмотрен потенциал бактериоцинов в аквакультуре для контроля заболеваний (включая патогены *Vibrio* spp., *Aeromonas* spp., *Yersinia ruckeri*), улучшения качества воды и консервации кормов.

Заключение. Бактериоцины представляют собой экологичную альтернативу традиционным антибиотикам для повышения продуктивности и устойчивости агро- и аквасистем. Реализация их потенциала требует решения задач, связанных с оценкой эффективности in vivo, разработкой систем доставки, изучением рисков развития резистентности и преодолением регуляторных барьеров.

Ключевые слова: бактериоцины; устойчивое сельское хозяйство; контроль заболеваний в аквакультуре; рыбные патогены; пробиотики; почвенные бактерии

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Introduction

In addition to antibiotics' use in the medical field, they are also widely used in the agro-industrial sector [59; 111]. The intensive development of crop production, animal husbandry and aquaculture require their use to increase yields, treat and prevent infections [61; 86], as well as growth stimulants in feed (in controlled doses) [24]. The use of antibiotics in agriculture is global and extremely uneven. China accounts for about half of the global volume, followed by the USA, Brazil, India and Germany [53]. In 2010, China was the largest consumer of veterinary antimicrobials (approximately 30% of global production) [50]. According to the Van Boeckel et al. (2015), by 2030, the consumption of antibiotics in densely populated countries will increase by 67%. The widespread use of antibiotics, although it helped meet the growing demand for agricultural products, led to negative environmental consequences, such as the emergence of antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARG) [111; 118]. In this regard, the issue of finding alternatives to the use of antibiotics in agriculture becomes urgent [4; 116], one of which may be the use of probiotic bacteria and bacteriocins [7; 81], in aquaculture inclusively [75].

Bacteriocins are a heterogeneous group of ribosomally synthesized antimicrobial peptides. They are of great interest as a strategy for overcoming antibiotic resistance [26]. Having a wide spectrum of action and diverse biochemical properties [103], bacteriocins provide a competitive advantage to producing bacteria [115], which makes them and pro-ducing probiotics promising for use. The relevance of the approach is also confirmed by the growing losses in aquaculture due to bacterial diseases, where the use of bacteriocins is being investigated due to their activity against gram-positive and gram-negative bacteria [83]. Despite the potential, the introduction of bacteriocins (including use with probiotics in feed) requires a detailed approach to safety assessment to risk minimization.

Soil ecosystems have the highest microbial diversity on Earth, where intense competition drives the evolution of powerful antimicrobial compounds. The genera *Bacillus, Pseudomonas,* and *Streptomyces* are producers of structurally diverse bacteriocins [94]. Biostimulators of growth are one of the possible applications derived from soil ecosystems of bacteriocins [93]. In a study by the Subramanian (2014), it was indicated that the effective concentration of bacteriocins for stimulating plant growth is approximately nanomolar, which makes them an economically advantageous alternative for reducing the use of fertilizers and agrochemicals. Bacteriocins can act as an alternative to antibiotics in agriculture to combat pathogenic and antibiotic-resistant bacteria, especially zoonotic strains [63]. In particular, bacteriocinogenic *Escherichia coli* demonstrates antagonistic activity against resistant strains isolated from animals and can reduce dependence on antibiotics in animal husbandry. However, successful application requires an in-depth study of the mechanisms of action and effectiveness of bacteriocins in vivo. Peptides of terrestrial origin demonstrate effectiveness, including against aquatic pathogens, which indicates the selectivity of their molecular targets in different ecological niches [19].

Purpose. This review aims to synthesize current knowledge on the potential of bacteriocins as viable alternatives to conventional antibiotics in agriculture and aquaculture. It seeks to elaborate on their classification, mechanisms of action, the principal bacterial genera involved in their production, and their practical applications in enhancing plant growth, controlling livestock diseases, and managing pathogens in aquaculture systems.

Materials and methods

This article is a comprehensive narrative review. The data were gathered through an extensive examination of the scientific literature. The methodology involved identifying relevant studies via academic databases using keywords such as "bacteriocins," "agriculture," "aquaculture," "probiotics," and "antimicrobial peptides." The selected literature was then analyzed to extract information on bacteriocin characteristics, producer organisms, mechanisms of action, and documented applications in the specified fields. The synthesis of this information provides a state-of-the-art overview intended to highlight both the current achievements and future challenges in bacteriocin research and application.

Results

In natural conditions, bacteria compete for resources using a variety of survival strategies, including the synthesis of antimicrobial compounds such as bacteriocins [15; 18]. Bacteriocins are protein molecules characterized by a high specificity of action directed mainly against close competitor strains [32]. This mechanism helps to reduce the number of related bacteria and enrich the microbial community with taxons carrying new genes, which ultimately increases the biodiversity and functional efficiency of the community [102]. Secreted by both gram-positive and gram-negative bacteria, bacteriocins exhibit significant structural and genetic diversity, as well as variability in biochemical properties, mechanisms of action, and specificity to target cellular receptors [27]. Unlike broad-spectrum antibiotics, bacteriocins have a narrow specificity, selectively inhibiting certain strains with minimal effect on the autochthonous microbiota, and exhibit high activity in low concentrations [98].

In the food industry, bacteriocins are used as natural bioconservants (for example, low-grade L*actococcus lactis*) to increase the shelf life of products [62; 69, 88] which can be used to increase the shelf life of feed. The potential of their medical use is confirmed by data from preclinical and clinical studies [42], which in turn shows their effect on pathogenic organisms.

It should be noted the importance of bacteriocins' action in the rhizosphere, where they inhibit the development of phytopathogens, reducing plant morbidity, and promoting their productive growth. Synthesized by rhizospheric microorganisms, bacteriocins are an environmentally friendly alternative to chemical pesticides [38]. The expression of bacteriocin genes is regulated by bacteria in response to stress factors and intercellular interactions, including activation through quorum sensing systems upon reaching high cell density [9; 68].

In recent years, there has been a significant increase in research interest in rhizobacterium bacteriocins due to their high biotechnological potential as agents of biological control of phytopathogens or biostimulators of plant growth [33].

Throughout the history of research devoted to bacteriocins, their classification has been one of the most controversial issues. Figure 1 shows one of the approaches to bacteriocins' classification [120].

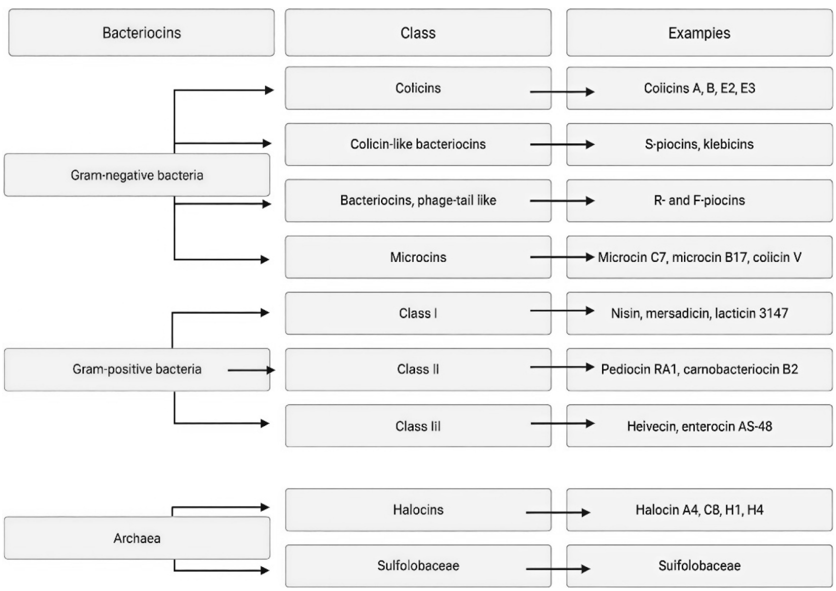

Fig. 1. Classification of bacteriocins

The initial systematization of bacteriocins was based on their division into two classes: class I includes lantibiotics, peptides that have undergone posttranslational modification to form lanthionine, whereas class II unites bacteriocins consisting of unmodified amino acids [25].

Güllüce et al. (2013) and Mokoena (2017) describes the formation of well-known classifications based on various characteristics, such as the type of producing bacteria, molecular characteristics, and mechanisms of action. Modern classifications [10] integrate genetic and structural-functional criteria, including the concept of RiPP (ribosomally synthesized and post-translationally modified peptides), covering lantibiotics and related compounds.

Just as in the classification, there was no consensus on the principles of bacteriocins' action. For example, Solis-Balandra and Sanchez-Salas (2024) describes the possible mechanisms of their action. Bacteriocin PLNC8 exhibits inhibitory activity against *Helicobacter pylori*, but the mechanism of action remains unclear [55]. At the same time, for some groups of bacteriocins produced by lactic acid bacteria (LAB-bacteriocins), the mechanisms have been thoroughly studied [89]. Lantibiotics carry out bacteriolysis in two ways: disruption of cell wall synthesis and pore formation. In the first case, lantibiotics inhibit wall synthesis either by binding to lipid II (a key intermediate in the transglycosylation reaction, as in gallidermin [64], or by blocking the incorporation of glucose and D-alanine into peptidoglycan precursors (although this process also depends on the presence of lipid II) [64]. The mechanism of pore formation is a violation of the integrity of the cell membrane. Another well-studied group are colicins produced by *E. coli*, which act against gram-negative bacteria. Their tertiary structure includes three functional domains: receptor (for binding to the membrane), translocation (for penetration into the cell) and toxic. The toxic domain implements its action through the formation of potential-dependent pores in the inner membrane, nuclease activity against genetic material, or inhibition of peptidoglycan synthesis. However, the specific ways of implementing these mechanisms may vary [60].

Sharma et al. (2021) described detailed mechanisms of action in the study. Bacteriocins suppress pathogenic bacteria by forming pores in the membrane, inhibiting the synthesis of the cell wall, nucleic acids and proteins. One of these mechanisms of action is shown in Figure 2. As a rule, these substances have a narrow spectrum of antimicrobial activity, acting mainly on closely related species. However, some bacteriocins exhibit a wide spectrum of action, effective also against phylogenetically distant bacteria [51]. Their main biological role is to protect the producer: they limit the growth of competing strains or prevent the invasion of other bacteria, thereby providing an advantage in the ecological niche [82].

The use of bacteriocins, due to their properties and principles of action, covers several important areas. Increasing the shelf life of products through the suppression of pathogens and bacteria in the food industry [34]. Bacteriocins act as biocontrol agents, promoting plant growth and development, as well as increasing yields [12]. Antimicrobial activity against pathogens makes it possible to use it as a probiotic to maintain human health and enhance immunity [106]. In addition, they are used in veterinary medicine, the production of feed additives, contribute to productivity in poultry and pig farming (Schofs et al., 2020), aquaculture and are effective against animal pathogens.

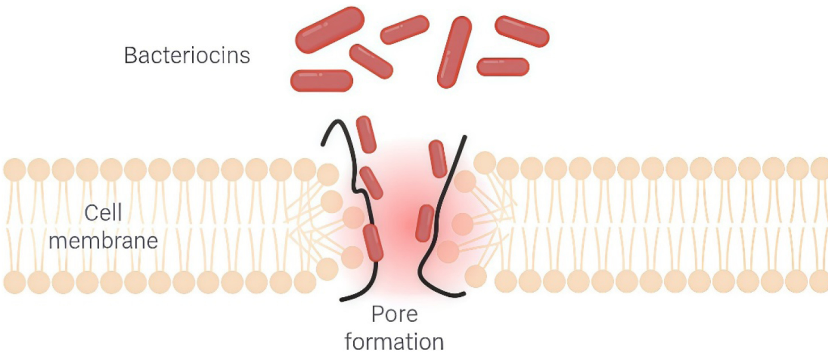

Fig. 2. The mechanism of action of bacteriocins through the formation of pores

Soil as a source of bacteriocinogenic bacteria

Investigations over the years have focused on the issue of studying soil bacteria that produce bacteriocins [36; 41; 108; 114]. The range of studied bacterial species (bacteriocins) is quite wide and diverse. The bacteria studied by a number of authors (and their bacteriocin derivatives) are shown in Table 1.

Table 1.

Bacteriocin-producing bacteria and their characteristics

Bacterium	Bacteriocin	Functions	Target organism	References
Bacillus brevis Bb	Bacillocin Bb	Protection against undesirable bacteria	*S. aureus, M. luteus, C. diphtheriae, C. xerosis and C. hoffmanni*	(Saleem et al., 2009)
Pseudomonas aeruginosa Pa	Pyocin Pa	Protection against undesirable bacteria	*S. aureus, S. epidermidis, S. pyogenes, E. faecalis, M. luteus, C. diphtheria, C. xerosis and C. hoffmanni*	(Saleem et al., 2009)
Bacillus licheniformis VPS50.2	licheniocin 50·2	Active against Gram-positive bacteria	*Listeria monocytogenes, methicillinresistant Staphylococcus aureus (MRSA) and β-haemolytic streptococci*	(Berić et al., 2014)

Bacillus altitudinis ECC22	Pumilarin, altitudin A	Suppression of growth and reproduction of pathogenic and competitive microorganisms	*Bacillus safensis LTh12; Bacillus pumilus PE12; Listeria monocytogenes CECT 4032; Pediococcus damnosus CECT 4797;* and other gram-positive bacteria	(Lafuente et al., 2024)
Bacillus cereus Bc7	Cerein 7	Antibacterial activity against Gram-positive bacteria	*Listeria innocua G244; Micrococcus luteus ATCC 7468 and Staphylococcus aureus ATCC 12600*	(Oscáriz and Pisabarro, 2000)
Bacillus thuringiensis BUPM4	Bacthuricin F4	Antibacterial activity against Gram-positive bacteria	*Bacillus thuringiensis subsp. Kurstaki; Bacillus cereus; Bacillus subtilis; Bacillus ureus; Bacillus licheniformus; Enterobacter cloacae*	(Kamoun et al., 2005)
Rhizobium	Rhizobium leguminosarum bv. viciae LC-31	Produce antimicrobial activity, which inhibited the growth of the related strains	*R. leguminosarum bv. Viciae; Agrobacterium sp*	(Hafeez et al., 2005)
Bacillus. sphaericus strain SOPB1	-	An alternative source for the production of peptide antibiotics; inhibit methicillin resistance	Bacteriocin exhibits high antagonistic activity against MRSA, *S. aureus* and *B. subtilis*	(Aunpad et al., 2011)
Bacillus subtilis L-Q11	Subtilin L-Q11	It is able to inhibit the growth of various Gram-positive bacteria, retains more than 96% of its antibacterial activity after pasteurization and more than 58% after high-temperature sterilization, demonstrates activity in the pH range from 2 to 9	*B.amyloliquefaciens, L. lactis, L. plantarum, S. aureus, E. faecalis, S. aureus ATCC 29213, Bacillus spp*	(Qin et al., 2019)

Brevibacillus	Brevibacillus reuszeri (B12) и Brevibacillus formosus (B22)	Against various pathogenic bacteria and fungi	*Salmonella typhi, Bacillus cereus*	(Gholizadeh et al., 2013)

The genus *Streptomyces* is a gram-positive, predominantly soil saprophytic bacteria [17] that forms branching mycelium and stable spores, which contributes to their survival in adverse conditions [85]. Although individual species may be plant pathogens [5] or rare human pathogens, their key ecological role is related to the production of bacteriocins. The ability to produce a wide variety of these substances [45] provides Streptomyces with an antagonistic effect against competing microorganisms and pathogens. They also play a fundamental role in regulating soil microbial communities, suppressing the growth of undesirable organisms and maintaining ecological balance. The large-scale production of secondary metabolites due to the large size of the genome and its features [48] explains the growing interest in Streptomyces as potential probiotics or sources of biocontrol agents.

Yanagida et al. (2006) conducted a study on the isolation of lactic acid bacteria producing bacteriocin from soil in Yamanashi Prefecture, Japan. 42 strains of acid-producing bacteria were isolated from 55 soil samples. Three isolates showed antibacterial activity against *Lactobacillus sakei* JCM 1157 T: *Lactobacillus* animalis C060203, *Enterococcus durans* C102901, and subspecies *Leuconostoc mesenteroides* C060204. Bacteriocins from *L. animalis* C060203 act on 18 gram-positive bacteria. Bacteriocins from *L. robustus* C102901 has high temperature resistance and can be used as bioconservants.

Research by Saleem et al. (2009) is aimed at identifying and characterizing bacteriocins produced by soil-associated microorganisms (*Bacillus brevis* Bb (gram-positive) and *Pseudomonas aeruginosa* Pa (gram-negative)). Bacteriocins are produced by various bacterial species such as *Bacillus* spp., *Pseudomonas* spp., *Staphylococcus aureus* and others. They were tested against Gram-positive bacteria, and the maximum production was observed at a temperature of 32°C in a BHI environment. Both bacteriocins are stable at pH 1-9 and 1-11, respectively, and resistant to high temperatures (100°C for 30 minutes). The activity of bacteriocins is lost after treatment with proteinase K, which indicates their protein nature.

In addition to the soil bacteriocins themselves, studies have been conducted on bacteriocin-like extracellular metabolites (BLEM) with pronounced antagonistic activity against phylogenetically similar strains [2]. BLEM were obtained from *Bacillus subtilis* SF8 and *Pseudomonas aeruginosa* SF4. They demonstrate high stability under extreme conditions: The *B. subtilis* SF8 metabolite retained 71%, 92%, and 80% activity after 60-minute incubation at 90°C, pH 4, and pH 10, respectively, while the *P. aeruginosa* SF4 BLEM retained 91%, 81%, and 89% activity under the same conditions. Ultraviolet irradiation enhanced the activity of *P. aeruginosa* SF4 BLEM, but did not affect the activity of the *B. subtilis* SF8 metabolite. IR-Fourier spectroscopy (FTIR) data indicate that BLEM *B. subtilis* SF8 and *P. aeruginosa* SF4 damage the cell membranes of the indicator strains *Bacillus macerans* SF2 and *Pseudomonas fluorescens* BS2, respectively. Partially purified BLEM preparations also showed a wide range of inhibitory effects against the tested bacterial and fungal pathogens.

The study conducted by He et al. (2006) also examined bacteriocin-like peptides produced by *Bacillus licheniformis* ZJU12. The peptides showed broad antagonistic activity against various types of gram-positive bacterial and fungal pathogens, but not against gram-negative bacteria, with the exception of *Xanthomonas oryzae pv. oryzae* (the causative agent of rice diseases). Activity was stable at temperatures up to 100°C for 30 minutes, but completely lost at 121°C in 15 minutes. In the pH range from 2 to 9, with an optimal value of about 6.5.

The most significant and well-studied genera of soil bacteriocin-producing bacteria are *Bacillus*, *Streptomyces*, and *Pseudomonas*. However, the ability to produce these antimicrobial peptides is widespread among many other soil inhabitants, including *Paenibacillus, Serratia, Enterobacter/Pantoea, Stenotrophomonas*, and *Burkholderia*. The study of soil bacteriocins is critically important for understanding microbial ecology and developing new strategies for biocontrol and antimicrobial therapy.

Bacteriocins in aquaculture

The uncontrolled use of antibiotics in aquaculture (including their use as growth stimulants) to prevent infections has led to their spread in the environment [35]. This creates selective pressure on microbial communities, contributing to the development and spread of AMR [77]. Resistant bacteria form ARG reservoirs, turning aquaculture systems into AMR "hot spots", which makes the study of aquaculture resistance critically important [107].

The transfer of antimicrobial resistant genes to human pathogens is an important negative factor for research. Transmission mechanisms can be either direct (through common zoonotic pathogens (for example, Vibrio spp.) or indirect transmission (horizontal gene transfer). Bacterial infections pose a serious threat to the aquaculture industry, causing massive epizootics and significant economic losses. Disease control directly de-pends on the use of vaccines [91; 117], antibiotics, and chemotherapy, but these methods pose risks to animal health and the sustainability of aquatic ecosystems, as well as indirectly to human health

[6]. In this context, bacteriocins produced by probiotic strains represent a safe alternative. Understanding the mechanisms of their antimicrobial action against aquaculture pathogens is critically important for developing effective preventive strategies. Some of the known pathogens are shown in Table 2.

Table 2.

Bacteriocin-producing bacteria and their characteristics

Disease	Causative agent	Affected objects	Distribution / Features	Key control issues	References
Vibriosis	Vibrio anguillarum (O1, O2a), Aliivibrio salmonicida, V. ordalii, V. harveyi	Marine fish (salmon, sea bass, dorado, etc.)	Global. The severity depends on the strain, age of the fish, and environmental conditions.	The need for new vaccine delivery methods for mass immunization	(Woo et al., 2002; Jayasree et al., 2006; Bowser, 1999; Mohamad et al., 2021)
Yersiniosis	Yersinia ruckeri (Biotypes 1, 2; Serotype O1)	Rainbow trout, Atlantic salmon, etc.	Fresh and sea water	Threat to trout farming; vaccines against different biotypes are needed	(Moeller, 2005; Toranzo et al., 2009; Yang et al, 2021)
Enteritic sepsis of catfish	Edwardsiella ictaluri	Channel catfish, pangasius	High pathogenicity for catfish	Development of safe and effective vaccines for juveniles	(Moeller, 2005; Toranzo et al., 2009, Klesius and Shoemaker, 1999; Abdelhamed, et al., 2018; Triet et al, 2019)
Bacterial disease of cold-water fish	Flavobacterium psychrophilum	Salmon (young rainbow trout)	The cause of mass death of juveniles	Lack of commercial vaccines. Low efficiency of approaches	(Yimer Muktar et al., 2016, Toranzo et al., 2009, Takeuchi et al., 2021)
Mycobacteriosis	Mycobacterium marinum	>200 species of fish (sea bass, tilapia, salmon, etc.)	Chronicity. It is dangerous for sea bass in the Mediterranean and the Red Sea.	Lack of vaccines. Treatment complexity (chronic, intracellular)	(Bowser, 1999; Toranzo et al., 2009; Colorni, 1992; Diamant et al., 2000)
Bacterial kidney disease	Renibacterium salmoninarum	Salmon family	Chronic systemic infection. High mortality rate. Vertical transmission	Complexity of vaccine development (vertical transmission, intracellular parasitism)	(Yimer Muktar et al., 2016, Toranzo et al., 2009; Newman, 1993; Delghandi et al., 2020)

One such solution may be the use of lactic acid bacteria bacteriocins (LAB). They are used in aquaculture in three key areas [115]. Firstly, their inclusion in feed for aquatic organisms suppresses the growth of harmful microflora in the feed itself, prolongs its shelf life, and inhibits pathogenic bacteria in the body of animals, contributing to an in-crease in their immunity. Secondly, the use of bacteriocins as a component of probiotic preparations for the treatment of reservoirs can improve water quality. Their use minimizes the disturbance of the microecology of the growing environment and can increase feed consumption by aquatic organisms. Thirdly, the addition of LAB or the cultures producing them themselves as bioconservants during storage and transportation of aquatic organisms suppresses the development of pathogens and the formation of biogenic amines, ammonia and trimethylamine oxide, which significantly prolongs the shelf life of products and increases their safety.

Bacteriocins isolated from soil genera such as *Stenotrophomonas, Leuconostoc* and *Staphylococcus* have diverse biological activity and their use is relevant in aquaculture, as indicated in Table 3.

Table 3.

Some bacteriocins isolated from the soil that are intended for use in aquaculture

Producing strain	Bacteriocin	Biological role	Reference
Pseudomonas putida BW11M1	Not named	Suppression of phyto-pathogens	(Parret et al., 2003)
Bacillus sp. TL12	Bacin A2	Suppression of biofilm formation	(Liu et al., 2022)
Stenotrophomonas spp.	Stenocins	Antimicrobial activity	(Liu et al., 2022)
Leuconostoc citreum ST110LD	ST110LD	Antimicrobial activity	(Paškevičius et al., 2022)
Staphylococcus aureus	BAC-IB17	Antimicrobial activity	(Woo et al., 2021)

Ansari et al. (2018) presents a wide list of probiotics used in aquaculture: *Lactobacillus, Enterococcus, Bacillus, Aeromonas, Alteromonas, Arthrobacter, Bifidobacterium, Clostridium, Microbacterium, Paenibacillus, Phaeobacter, Pseudoalteromonas, Pseudomonas, Rhodosporidium, Roseobacter, Streptomyces* and *Vibrio*. They promote the growth of aquatic organisms and act as preventive agents, mainly administered with feed [20]. The bacteriocins synthesized by them suppress pathogens (for example, *Aeromonas* spp.) and promote the viability of aquatic animals [95]. The antimicrobial peptide *Lactobacillus acidophilus* completely suppresses the highly virulent pathogen of aquaculture *A. hydrophila*, unlike probiotics and postbiotics, which only delay fish death by 3-4 days [71]. Recombinant bacteriocins, such as nisin Z, prevent the colonization of pathogens in rainbow trout (Oncorhynchus mykiss), while enhancing immune functions and improving growth rates [3]. Substances with bacteriocin-like activity (BLS) obtained by coculturing *E. faecium* MU8 with *A. veronii* effectively inhibit the key pathogens of Nile tilapia A. jandaei and A. veronii [23]. The strategy of co-cultivation of bacteriocin-inducing gram-negative strains with gram-positive producers is becoming a promising method for increasing biosynthesis [79], optimizing their use in aquaculture.

Conclusion

Bacteriocins represent a promising and sustainable alternative to the traditional use of antibiotics in order to increase the productivity and sustainability of ecosystems in agriculture and aquaculture. This is confirmed by its targeted activity against key phyto-, livestock and aquatic pathogens, its role in biocontrol and growth stimulation, as well as its ability to preserve products and water quality, minimizing disruption of beneficial microbiota. However, the realization of this potential faces the challenge requiring reliable testing beyond laboratory research, the development of effective delivery systems, under-standing the risks of resistance, and overcoming regulatory barriers. Successful implementation requires careful consideration of specific environmental factors, farm management, and pathogen profiles within each unique production system, along with interdisciplinary research to move from laboratory efficiency to practical, scalable solutions.

Conflict of interest information. The authors declare that they have no conflict of interest.

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