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Review Article

Microbial innovations in agriculture: interdisciplinary approaches to leveraging microbes for food sustainability and security

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ABSTRACT

Ensuring food security and promoting sustainability are huge global challenges that humanity must address. The field of microbiology presents promising solutions by leveraging the immense diversity and capabilities of microorganisms. These microscopic life forms play vital roles throughout the food production cycle, from enhancing soil fertility and boosting plant growth to controlling pests and diseases, facilitating food processing, and managing waste. Exploiting beneficial microbes can increase crop yields, improve nutrient bioavailability, and reduce reliance on synthetic agrochemicals, thereby contributing to environmental sustainability. Moreover, microbial biotechnologies enable the development of innovative food products, enhance food safety measures, and prolong shelf life, consequently minimizing food waste. Significantly, microbial-based solutions can be tailored to local contexts, fostering inclusive and equitable food systems accessible to diverse communities. However, fully realizing the potential of microbiology in food systems requires a multidisciplinary approach, integrating advancements in microbial ecology, genomics, metabolomics, bio preservation, and biotechnology. This abstract explores the potential of microbiology to contribute significantly to food security and sustainability, emphasizing the importance of interdisciplinary research and the integration of microbiological innovations into agricultural practices and food systems.

1. Introduction

Ensuring food safety and security is crucial for building a sustainable future. Innovative approaches are needed to address future food sustainability and security challenges while adhering to food control standards and achieving SDGs. These goals include eradicating poverty and hunger, promoting clean water, responsible consumption, and production, and mitigating climate change in aquatic and terrestrial ecosystems. Strategies to achieve food security and sustainability include reducing food waste and losses, adopting plant-based diets, and conserving food resources. Balancing the trade-offs between food safety and security poses significant challenges.[1] Methods and tools ensuring food security must align with food safety, public health, and sustainability. Given the intricate and obscure nature of food systems, we recommend adopting a One Health approach to evaluate and achieve sustainable goals. In health security, food security involves creating systems to manage acute incidents from foodborne hazards, whether chemical or microbiological. Notably, systems preventing acute foodborne events, such as outbreaks, fundamentally resemble those addressing broader foodborne occurrences. Outbreak management systems are also used for sporadic foodborne cases and chronic foodborne diseases. Surveillance systems, especially those focused on acute risks, often prioritize microbiological hazards, yet chemical hazards significantly

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impact overall food safety. Therefore, data systems aimed at preventing foodborne diseases and contamination must include both chemical and microbiological hazards.[2] This paper examines food security, microbial diversity, food safety, and sustainability, following the framework of bio-preservation and antimicrobial resistance (AMR) management in food recovery contexts.

2. Microbial Diversity in Agriculture

Agriculture, humanity's oldest occupation, has evolved over centuries. Meeting the increasing hunger of a growing population demands more food from finite resources, requiring enhanced crop yields, resource conservation, and sustainable practices. For example, India's 1960s green revolution aimed to increase yields through agrochemicals, high-yield but nutrient-intensive crops, and inorganic fertilizers. These crops, susceptible to pests and diseases, necessitated chemical pesticides.[3] Although this approach boosted productivity, it degraded natural resource quality. India, once plagued by hunger, became a net food grain exporter, exceeding expectations. However, the widespread use of agrochemicals polluted crucial natural resources like the environment, water, and soil.[4] (Figure 1)

Integrating minimum tillage (MT) with natural farming effectively increases soil microbial biomass and abundance. Organic farming supports bacterial communities, which are more responsive to agricultural practices than other microbes. Combining organic farming with no-till (NT) practices enhances soil microbial characteristics more effectively than using either method alone or conventional tillage (CT). Additionally, no-till (NT) practices with cover crops boost substrate diversity, promoting soil enzyme synthesis crucial for nutrient cycling and soil health.[5]

The increased sugar consumption within the top 10 cm of soil is attributed to the abundant sugars and organic matter released from decomposing crop residues post-harvest. Researchers investigated the long-term effects of organic farming and minimal tillage (MT) on the diversity and structure of soil microbial communities, emphasizing the role of carbohydrates in sustaining and stimulating microbial activity in the rhizosphere compared to soil without plant roots. Their findings indicated positive outcomes, such as increased soil microbial biomass, higher total levels of phospholipid fatty acids (PLFA, markers of living microbes), and greater populations of mycorrhizae, fungi, and Gram-negative and Gram-positive bacteria. The study also noted an increase in Gram-positive bacteria, evidenced by higher muramic acid levels, a component of their cell walls. Additionally, minimal tillage led to a significant rise in both microbial biomass nitrogen content and fungal PLFA concentrations.[6] Nivelle et al. explored the combined effects of no-till (NT) with cover crops and nitrogen fertilization over five years in cereal and legume rotations (wheat, corn, pea, and flax).[7] Their research highlighted increased total nitrogen and organic carbon levels, along with improved functional activity and microbial diversity when cover crops were used with no-till practices. Conversely, conventional tillage (CT) negatively impacted soil carbon and nitrogen availability and enzyme activity.[8] Inclusion of only wheat straw caused a significant carbon-to-nitrogen ratio imbalance, an issue often ignored in traditional tillage. Numerous studies on tillage's impact on microbial populations have focused on: (a) analysing soil effects (biological and physicochemical) under different agricultural preparations; (b) investigating no-tillage methods for their potential to enhance microbial richness and diversity; and (c) exploring the relationship between soil nitrogen (N) or carbon (C) levels and microbial community composition.[9] Extended no-tillage (NT) use has significantly improved operational taxonomic units (OTUs) diversity, species richness, evenness, and the Shannon diversity index. Conversely, reduced Simpson diversity index values were observed compared to conventional tillage (CT), due to increased substrate availability from higher soil organic carbon content, fostering greater bacterial diversity.[10]

3. Plant Microbe Interaction

A growth-promoting microbial strain is valuable in agriculture, necessitating its effective reintroduction onto plants, successful establishment in the rhizosphere, and facilitation of nutrient movement to promote plant development. Validation of candidate strains can be achieved through plant-microbe interaction assays, assessing their ability to enhance plant growth and nutrient uptake.[11] Researchers seek optimal combinations of plant varieties and rhizobia strains for specific environmental conditions and soil types. Nitrogen fixation is not exclusive to legume-rhizobia symbiosis; nitrogenase genes are present in various bacteria. Non-leguminous plants also host nitrogen-fixing bacteria, expanding nitrogen-fixing symbiotic associations beyond traditional legume-rhizobia partnerships.[12] These findings indicate potential for optimizing plant-microbe combinations to enhance nitrogen fixation. Microbial mobilization of nitrogen from non-atmospheric sources has occasionally been reported to enhance plant growth. In certain experiments, researchers found that the nitrogen source contributing to increased plant yields was ammonium sulfate fertilizers rather than nitrogen from soil organic matter. Studies indicate that non-sterilized grass seeds could access and utilize nitrogen from protein sources more effectively than sterilized seeds. However, the specific bacterial strains responsible for this capability in non-sterilized seeds remain unidentified. Additionally, some research has demonstrated that the fungus Glomus intraradices can transfer organic forms of nitrogen to plants. Future research could aim to identify other fungal varieties with similar capabilities and characterize the associated mechanisms and genes. Numerous reports document fungal and bacterial strains that solubilize inorganic phosphorus and mineralize organic phosphorus sources. Many of these phosphorus-mobilizing microbes are also recognized as plant growth-promoting microorganisms. However, it is important to note that microbes can promote plant growth through various mechanisms, and it is sometimes unclear if phosphorus mobilization directly contributes to the growth promotion observed in these microbial strains. Research on a plant growth-promoting strain of Pseudomonas bacteria has shown that knocking out the sulfonate monooxygenase enzyme—which is involved in organic sulfur mineralization—plays a role in the growth-promoting effects of these bacteria. This emphasizes the importance of organic sulfur mineralization in plant growth and elucidates the mechanisms through which certain bacteria enhance plant development.[13] (Figure 1)

4. Microbial Processes in Food Production

The earliest use of microorganisms by humans in food systems was for fermentation, one of the oldest recorded food processes, dating to around 7000 BC or earlier. This practice emerged independently in various ancient cultures. Fermentation, along with smoking and salting, is essential for food preservation and crucial to the development of human civilizations. It also enabled the creation of diverse food products with unique tastes and flavors.[14] Fermented foods originated from diverse environments, leading to a variety of edible products, including dairy items like cheese and yogurt, alcoholic beverages like beer and wine, fermented soy-based foods like douche, natto, and soy sauce, as well as various fermented vegetables like sauerkraut and kimchi.[15] Advancements in refrigeration, preservation techniques, modern food processing, and the use of synthetic and natural preservatives, along with methods like freezing and vacuum sealing, have provided alternatives to traditional metabolic processes. However, recent studies highlight the numerous health benefits of microbes in food, reigniting interest in fermentation.[16] This renewed interest is fueled by the rising popularity of fermented foods and ingredients, influenced by the growing trend of plant-based diets and the increased availability of international cuisines. For example, kombucha, a traditional fermented tea from Manchuria, has gained global popularity due to its purported health benefits. Similarly, tempeh and tofu, fermented soybean products from China and Indonesia, have become widely consumed protein sources, particularly as meat alternatives.[17] Fermentation in food contexts refers to enzymatic changes in raw ingredients due to microorganisms, altering both physical and chemical properties. Byproducts from this process preserve food by inhibiting harmful microorganisms, extending shelf life, and enhancing nutritional value, texture, taste, and aroma. Fermented foods may benefit health, particularly through their impact on the gut microbiome, which is increasingly recognized for its role in overall health. While probiotic supplements are popular, their health benefits and ideal bacterial strain combinations remain debated. Certain fermented foods exhibit probiotic properties and promote gut health.[18] Fermentation increases the bioavailability of nutrients by breaking down food components, making them easier to digest and absorb. For example, lacto fermentation raises iron content through acid level and pH adjustments, enhancing iron solubility and absorption. Fermentation also improves nutritional quality by reducing antinutritional factors that hinder the availability of phytochemicals, carbohydrates, or proteins. For instance, fermentation reduces trypsin inhibitors found in legumes, cereals, and grains. The Glycemic Index (GI) measures how quickly carbohydrates raise blood sugar levels. Probiotic or fermented grains, grain-like foods, and dairy products are linked to lowering GI, thereby reducing blood sugar spikes after consumption. Lowering GI intake and response has benefits in reducing risk factors for conditions like type II diabetes and cardiovascular diseases.[19] Microbial communities can eliminate toxic substances and inhibit harmful microorganisms. Fermentative processes, for example, enzymatically degrade Aflatoxin, a common toxin in foods contaminated by Aspergillus flavus. Fermentation also lowers free radical levels in fruits and vegetables, enhancing safety and quality. Many microorganisms naturally produce beneficial compounds like antioxidants, polyunsaturated fatty acids, sphingolipids, conjugated linoleic acids (CLA), essential minerals, and vitamins.[20]

5. Bio Preservation

Bio-preservation extends food freshness by utilizing natural or controlled microbiota or antimicrobial agents. Fermentation byproducts and beneficial bacteria are often employed to control spoilage and neutralize pathogens. Animal-derived foods, due to their neutral pH, nutritional richness, and moisture, spoil quickly, necessitating effective preservation to maintain quality and safety. Insufficient preservation can lead to human illnesses and costly public health issues globally.[21] The food industry typically employs proper laboratory protocols and sanitary conditions to ensure safety and quality. However, proficient conservation through various methods is crucial. Preservation techniques range from cold storage (refrigeration and freezing) to heat-based methods (pasteurization and sterilization) and the use of specialized chemicals. Modern methods like hurdle technologies, irradiation, and bio-preservation are increasingly important. Unlike conventional methods that often alter food composition and reduce nutrients, contemporary techniques better ensure food quality and safety.[22] In today's interconnected food market,

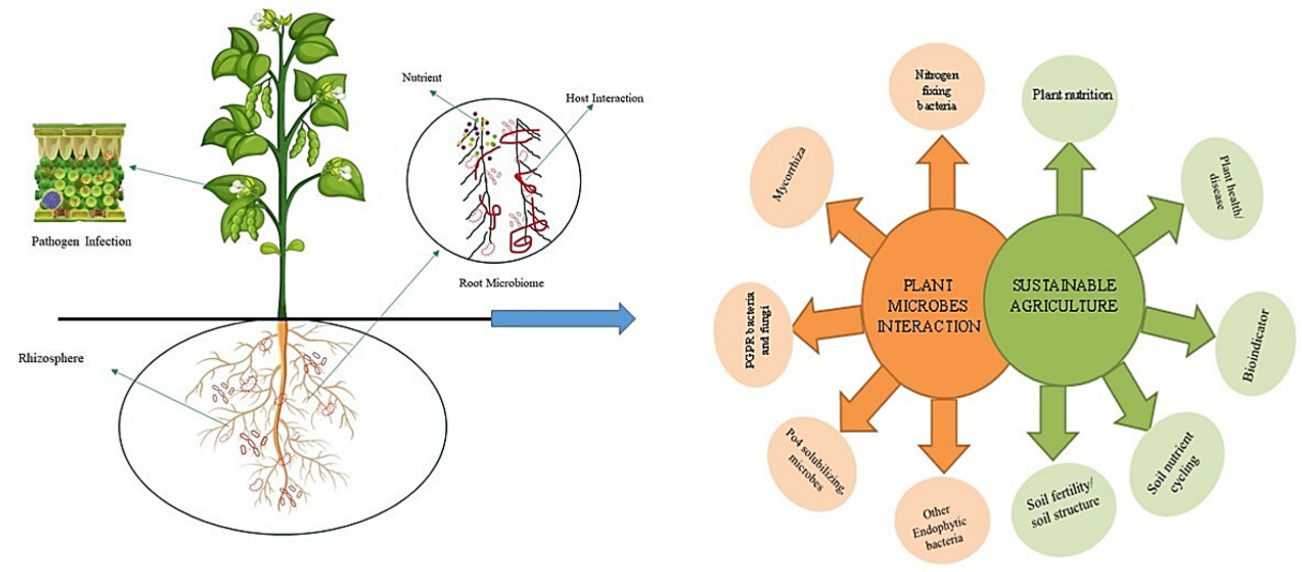

Figure 1: Plant microbe's interaction and involvement of microbes for food sustainability

with new food items and emerging technologies, there's a growing preference for minimally processed foods that offer convenience and extended shelf life. Bio-preservation, leveraging the antimicrobial properties of natural organisms and their byproducts, meets this demand. It bridges traditional and modern preservation methods, aligning with current food safety and quality standards. Bio-preservation's effectiveness relies on antibacterial systems like lactic acid bacteria, their bacteriophages, bacteriocins, and enzymes. These substances, used in the food industry to create desired textures and flavors, also help maintain food quality and safety. They are crucial natural preservatives in modern large-scale food production.[23] Research into using microbial communities and antimicrobial compounds to prolong food shelf life and edibility is advancing. Fermentation exemplifies this method, where microorganisms, either naturally present or deliberately added, are utilized. The goal is to enhance food preservation by generating beneficial compounds through microbial metabolism that inhibit spoilage and eliminate harmful microbes. This eco-friendly approach reduces waste and offers a sustainable alternative to conventional methods. Lactic acid bacteria (LAB) and their organic acid compounds, which have antimicrobial properties and enhance flavors and textures, are primarily used. Fermentation has been a food preservation method for centuries.[13] In the industrialised world, approximately 60 percent of food items undergo fermentation to ensure uniformity, quality, and safety. Utilizing native microbiota in controlled environments is preferred to achieve distinct textures and flavors in specific products. Although the dairy industry primarily benefits from microbiota, their usage extends to vegetable and meat products. Bio-preservatives utilized in food must be categorized as generally recognized as safe (GRAS), ensuring they pose no adverse effects on food. Biological agents employed in food preservation are generally categorized into two groups: protective cultures and starter cultures. Protective cultures, on the other hand, are primarily employed to regulate antimicrobial activity, thereby diminishing the survival and proliferation of pathogenic microorganisms in food. Starter cultures consist of specific microorganism groups employed to start fermentation, leading to the creation of compounds that give fermented products their unique texture and flavor.[22]

5.1. Chemical additive

Bacteriocins, such as nisin, display broad-spectrum antibacterial activity. The success of fermentation in food processing depends on pH, temperature, and the nutritional composition of the food. Challenges include reduced production over time, susceptibility to phages, and antagonistic interactions with other microorganisms. Bacteriocin effectiveness can be hindered by pathogen resistance, environmental conditions, slower diffusion, fat content, irregular distribution, and solubility within the meat matrix. Utilization in food requires production by GRAS microbes, thermostability, high activity, flavor enhancement, and adherence to safety standards for human consumption under GRAS regulations. Nisin, a commonly used bacteriocin, was introduced in the 1950s to counteract Clostridium tyrobutyricum, which causes late cheese blowing. Bacteriocins primarily suppress pathogenic and spoilage bacteria during food processing. Nisin's bactericidal effect is pH-dependent, increasing in potency as the pH decreases. This action is enhanced by *Lactobacillus* acidophilus proliferation.[24] suggesting that combining nisin with *L. acidophilus* is more effective than using either alone. Nisin, lacticin, pediocin-like bacteriocins, and enterocin AS-48 are commonly used as preservatives in vegetables, dairy, and meat products. These bacteriocins can be applied in three ways: in situ production by starter or protective cultures, during fermentation with a bacteriocin-producing strain, or as a purified or semi-purified additive. In situ production is often preferred for its cost-effectiveness. For instance, dairy starters modified to produce nisin are designed to inhibit *Staphylococcus aureus* in lactic curd and Clostridium tyrobutyricum in semi-solid cheeses.[25]

6. Food Safety and Microbial Pathogens

Redirecting food safety resources to areas with maximum One Health benefits is crucial. Without understanding the prevalence and impact of diseases linked to pathogens and food products, prioritizing areas for mitigating foodborne hazards is challenging. Major organizations like FAO, OIE, and WHO emphasize a health approach in tackling zoonotic diseases, as noted in A Tripartite Concept Note.[26] The OIE recognizes the socio-economic importance of zoonotic diseases and advocates for a One Health approach. Both UNICEF and the World Bank promote increased production and consumption of fermented foods. Although the types of zoonotic diseases vary significantly, they are best prevented through a comprehensive One Health strategy. This approach considers the entire farm-to-fork process, utilizing surveillance data across the food production chain and integrating it with human disease data in public health.[27] Such holistic preventive measures can reduce health and economic impacts on developing nations, offering significant improvements within the One Health framework. Several chemical hazards in food affect both humans and animals through direct consumption, contamination, or environmental exposure, warranting their inclusion in the health infrastructure. For instance, corn, a common food component, can become a source of aflatoxin toxic to both humans and animals if infected. Recent melamine contamination outbreaks in North America affecting pets and in China affecting children highlight the critical need for collaborative One Health inquiries.[28] In these cases, nephrotoxicity is a common issue. The broader concern revolves around chemical contamination in food, where pesticides and other substances are often improperly used in food production, leading to harmful residue levels in food products. Major contamination events often impact entire ecosystems and human populations. Therefore, One Health monitoring and surveillance systems must explicitly include chemical waste. Pesticides are crucial for protecting crops and reducing post-harvest losses, thus supporting food security. Their development was central to the Green Revolution, transforming modern agriculture. However, recent research highlights their negative environmental impacts. Misuse of pesticides and their presence in water as pollutants are growing global issues, causing significant environmental contamination and potential health risks for humans.[29] Antibiotics are crucial for treating bacterial infections, but some microorganisms have developed resistance mechanisms, making certain antibiotics ineffective. The antibiotics Azithromycin, Chloramphenicol, Ceftriaxone, Penicillin, Gentamicin, Amoxicillin, Tetracycline, and Cephalexin are known to be ineffective against microorganisms like *Escherichia coli*, *Listeria monocytogenes*, *Salmonella* spp., and *Staphylococcus aureus*. These bacteria counteract antibiotics by producing inactivating enzymes, altering cell membrane permeability, or modifying target sites. Understanding these resistance patterns is essential for selecting appropriate antibiotics and developing effective treatment strategies. Ongoing research is vital to address the threat of antibiotic resistance to public health.[30] (Table 1).

6.1. Control food borne pathogen

To prevent microbial proliferation or survival in food, strategies target manipulating optimal extrinsic and intrinsic conditions necessary for bacterial and fungal growth. Intrinsic factors pertain to the food's inherent characteristics, such as nutritional composition, water activity, pH, redox potential, and presence of natural antimicrobials. Extrinsic factors involve the surrounding conditions, including storage humidity and temperature. Natural antimicrobials hinder microbial growth by disrupting cell function and structure. This review classifies antibacterial and antifungal agents into two categories based on their source: chemical and biologically derived preservatives (Figure 2).

6.1.1. Chemical antimicrobials

Preservatives encompass more than just antimicrobials, although chemical antimicrobials are often labeled as preservatives. Antimicrobials inhibit microbial growth but may not eliminate microorganisms, targeting specific metabolic processes such as the cell membrane, genetic material, and cell wall. Different agents use various mechanisms to inhibit microbial growth, and their combination can yield a synergistic effect. Conventional chemical antimicrobials, with a long history of use and approval in many countries, include nitrites and sulfites. Organic acids like sorbic, benzoic, acetic, propionic, and lactic acids are also common food preservatives. In their undissociated state, these acids permeate the lipid bilayer of the cytoplasmic membrane and enter the cytoplasm, where they dissociate into protons and anions, lowering the intracellular pH and inhibiting glycolysis and active transport. Bacteria use cellular energy to expel protons,

Table 1: Microorganisms isolated from animal-derived food and antibiotic resistance

Food sample source	Microbes	Resistant for antibiotics	
Bovine milk sample	*Escherichia coli*	Azithromycin, Chloramphenicol, Ceftriaxone, Penicillin, Gentamicin, Amoxicillin, Tetracycline, Cephalexin	(Cornelius et al., 2024)[31]
Bovine milk sample	*Listeria monocytogenes*	Azithromycin, Chloramphenicol, Ceftriaxone, Penicillin, Gentamicin, Amoxicillin, Tetracycline, Cephalexin	(Cornelius et al., 2024)[31]
Bovine milk sample	*Salmonella* spp.	Azithromycin 8 Chloramphenicol 6 Ceftriaxone 5 Penicillin 21 Amoxicillin 15 Tetracycline 5 Cephalexin	(He et al., 2020)[32]
Bovine milk sample	*Staphylococcus aureus*	Azithromycin 8 Chloramphenicol 6 Ceftriaxone 6 Penicillin 21 Gentamicin 3 Amoxicillin 25 Tetracycline 7 Cephalexin	(Muteeb et al., 2023)[3]
Pigs	*E. coli*	β-lactams	(Muteeb et al., 2023)[3]
Pigs	*S. aureus*	Methicillin	(Silveira et al., 2021)[8]
Pork	*E. coli*	Ampicillin, Erythromycin, Tetracycline, Chloramphenicol, Ciprofloxacin	(Cornelius et al., 2024)[31]

suggesting the antimicrobial effect of organic acids stems from this process. However, traditional antimicrobials raise concerns, as some may pose health risks (e.g., nitrites have been linked to increased cancer risk in children), affect essential nutrients, or alter food flavor. For instance, sulfites can degrade essential vitamins like thiamine.[33] Natural food preservatives are primarily organic compounds from natural sources, including essential oils, spices, lactoferrin, garlic oil, phenolic compounds, avidin, lysozymes, and isothiocyanate.[34] While chemical preservatives effectively extend food shelf life, they have disadvantages.[35] Naturally occurring antimicrobials, such as those in spices, are present in small quantities, and higher levels may alter food flavor and aroma. Chemical antimicrobials are crucial in managing microbial toxins in foods, which are primarily derived from bacteria or molds. Toxins from foodborne pathogens can be heat-labile or stable.[12] Research shows that plant-based compounds can reduce bacterial toxin production by suppressing toxin-producing gene expression.[36,37] Numerous molds produce mycotoxins, such as aflatoxins from Aspergillus flavus, posing health risks to humans, animals, and birds. Mycotoxins like patulin, ochratoxin A, zearalenone, aflatoxins, and fumonisins are often found in cereals, causing various human illnesses.[37] Strategies to prevent mycotoxicosis, a condition from mycotoxin exposure, focus on reducing mold or spore loads. Chemicals like hydrogen peroxide are effective in neutralizing mycotoxins, such as aflatoxins. Currently, there are no approved methods for assessing antibacterial and antifungal efficacy in foods, leading companies to develop their own validation procedures.[35] Consumer preference for fresh-like foods and food safety concerns could drive scientific research and industrial shifts towards natural antimicrobials.

6.1.2. Biologically based preservatives

Antimicrobials originating from biological sources, mainly microbes, often employ lactic acid bacteria (LAB) or their byproducts to inhibit harmful microorganisms, thereby enhancing food quality and safety. LAB naturally preserves food through fermentation, a method favored by consumers who view them as natural and healthful preservatives. Integrating LAB into food products generates lactic acid, which aids preservation by acidifying the environment. The efficacy of LAB in producing lactic acid is influenced by factors like fermentable carbohydrates, initial pH levels, and LAB strain growth characteristics.[38] Besides lactic acid, other LAB-synthesized compounds such as diacetyl, hydrogen peroxide, and bacteriocins can inhibit foodborne pathogens. Microbial-derived antimicrobials also show potential in reducing mycotoxins in foods. For instance, biological methods to control aflatoxins in corn involve replacing toxigenic strains with non-toxigenic ones. Various Lactobacillus strains effectively manage aflatoxins, and modern genetic engineering techniques are being used to address aflatoxins via high-throughput methods. Bacteriocins, antimicrobial proteins produced by LAB strains, do not harm the producing bacteria and are synthesized ribosomally Typically, bacteriocins target Gram-positive bacteria, though some also affect Gram-negative bacteria. They primarily disrupt the target bacteria's cell membrane, increasing permeability and releasing ions and molecules. These attributes are expanding their use in improving food safety.[39] Nisin, a widely recognized bacteriocin, is approved in about fifty countries

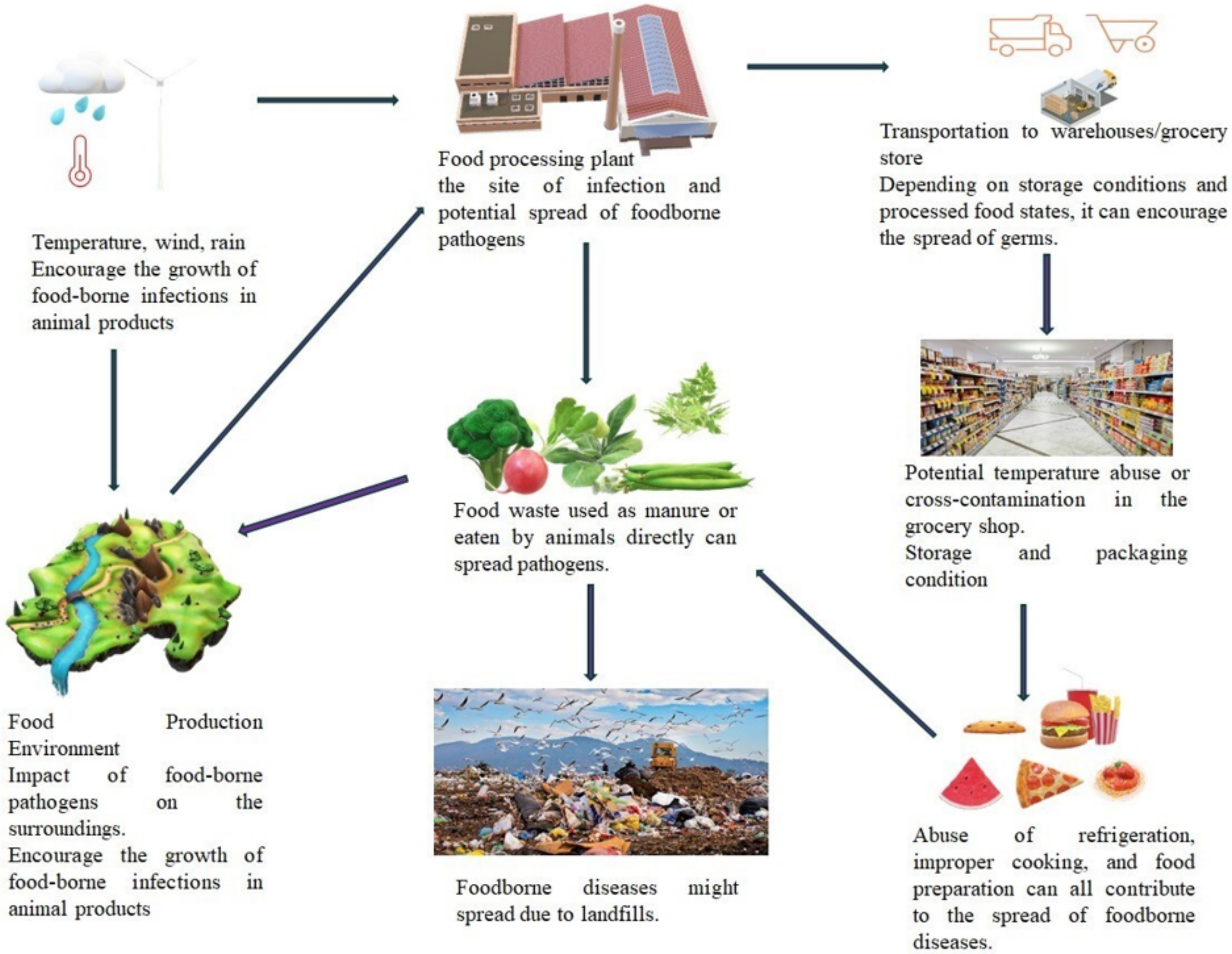

Figure 2: Controlling of food borne pathogen

and used as a preservative in processed vegetables, canned goods, and fresh cheese. It inhibits a broad spectrum of Staphylococci and prevents spore germination in Clostridium and Bacillus species. For example, introducing *L. lactis* into a cheese model prevented spore outgrowth in *C. beijerinckii* INIA. Additionally, when meat inoculated with *Listeria monocytogenes* was stored at 5°C, nisin delayed its growth for over two weeks and inhibited *Staphylococcus aureus* growth under the same conditions. Pediocin, another bacteriocin produced by *Pediococcus* spp., also shows antagonistic effects against Gram-positive and some Gram-negative foodborne pathogens. Ongoing research for novel bacteriocins, potentially as effective as or surpassing nisin or pediocin, is a growing area in food safety.[18,40,41]

Bacteriophages are viruses that invade bacteria, reproduce within them, and, in lytic cases, cause cell lysis.[42] Recently, significant interest has emerged in using bacteriophages to control foodborne pathogens and preserve food products due to their specificity and effective action. Key advantages of using lytic bacteriophages include their minimal impact on food sensory qualities and their wide availability.[43] Increasing evidence supports the effectiveness of bacteriophages in managing pathogenic, biofilm-forming microorganisms and spoilage, offering promising potential for their use. Numerous bacteriophages have been identified and applied in various food sectors to target both Gram-positive (e.g., *S. aureus* and *L. monocytogenes*) and Gram-negative (e.g., *Salmonella* spp., *E. coli* O157:H7, and *Pseudomonas syringae*) bacterial pathogens. The efficacy of bacteriophages in food preservation depends on the specific food environment and the concentration of bacteriophages used. For example, bacteriophages DT1 and DT6 completely eliminated *E. coli* O157:H7 in milk, while a cocktail of bacteriophages sprayed on spinach leaves significantly reduced 4.5 log colony forming units (CFU)/blade.[27,44] Bacteriophages generally demonstrate greater efficacy in liquid foods than in solid ones, though exceptions exist. Higher concentrations of bacteriophages, typically measured in plaque-forming units (PFU), are associated with increased inactivation rates of foodborne pathogens. Several commercial bacteriophage products, such as List-Shield^{TM}, SalmoFresh^{TM}, and EcoShield^{TM} (from Intralytics, Columbia, MD, USA), have been approved for use in food processing to target *E. coli*, *L. monocytogenes*, and *Salmonella* spp., respectively. Further research is needed to enhance bacteriophage effectiveness in food settings by improving their antimicrobial properties and reducing the time required to attach to and eliminate foodborne pathogens.

7. Probiotics and Gut Microbiota

The human gut contains a diverse range of microorganisms, including harmful pathogens and beneficial probiotics. An imbalance in gut microbiota caused by pathogens can increase disease risk.[45] Research indicates that probiotics can protect the digestive system by inhibiting bacterial pathogen growth. Consequently, the scientific community has focused on studying probiotics' effects on pathogen control in the gut and understanding the underlying mechanisms.[46] Probiotics employ various strategies to inhibit pathogens, such as enhancing epithelial barrier function, producing antibacterial substances, restricting pathogen access to nutrients, and outcompeting them for binding sites. A notable advantage of probiotics is their competitive exclusion of pathogens. For instance, probiotic *Escherichia coli* produces DegP, a periplasmic protein that inhibits enterohemorrhagic *E. coli* (EHEC) and surpasses pathogenic biofilms in dual-species biofilm formation.[16] Additionally, probiotics release antimicrobial substances, compete for attachment sites and nutrients, and impede Helicobacter pylori adherence to epithelial cells. The production of antimicrobial compounds is another crucial probiotic function.[13] Probiotics produce organic acids like propionic, acetic, and butyric acids through carbohydrate fermentation, which are primary antimicrobial agents against pathogens. These acids exhibit antibacterial properties by lowering pH and through undissociated acid molecules. Some studies suggest that probiotics may also eliminate intestinal pathogens by disrupting their signaling systems.[47]

8. Prospects for Addressing Antimicrobial Resistance (AMR) in Food

Ensuring food safety is fundamental to the food system, directly affecting product quality and customer satisfaction. The Hazard Analysis and Critical Control Points (HACCP) framework revolutionized the industry. The Food Safety Management Program adopts a proactive approach, addressing all aspects of food processing within a comprehensive safety framework to safeguard consumers by identifying and controlling hazards at each production stage.[48] Many industries have adopted food safety programs to monitor their supply chains, meticulously assessing risks that could compromise product safety. Common hazards include inadvertent microbial or chemical contaminations during production stages. However, these programs often overlook potential adulteration or deliberate contamination, which are more challenging to detect and mitigate.[49] Food fraud, or economically motivated adulteration (EMA), encompasses deceptive practices like adulteration, dilution, imitation, falsification, alteration, intentional substitution, or misrepresentation of a product, its components, or packaging, primarily for economic gain. While historically linked to less regulated markets, the prevalence of such practices has risen due to globalization and market expansion, complicating the verification of product integrity throughout traceability. Throughout the journey from manufacturers to end consumers, products are especially susceptible to adulteration, which complicates endeavors to guarantee authenticity and safety. Food fraud indirectly endangers consumers through unauthorized substances like antibiotics. Antibiotic residues in food, a significant instance of such fraud, pose substantial risks. These residues are often found in various common foods, predominantly from animal products, but also in processed goods available in markets. For example, significant quantities of mislabeled honey imported into the United States tested positive for antibiotics and were still sold. In developing nations, higher incidences of antibiotic residues in food result from less stringent regulations and fewer educational resources compared to developed countries. Establishing standardized antibiotic use regulations in agriculture is challenging due to regional differences.[50] Regulatory agencies, such as the European Food Safety Authority and the World Health Organization (WHO), have worked to develop standards tailored to specific countries to enhance antibiotic regulation. These standards include Acceptable Daily Intake (ADI), Withdrawal Period, and Maximum Residue Level (MRL), aiming to harmonize regulations globally. Despite efforts to regulate MRLs through guidelines from organizations like The World Trade Organization and the Codex Alimentarius, managing antibiotic residue remains difficult due to geographical discrepancies in MRL values. Inadequate policies on responsible antibiotic use in human and animal populations have contributed to the rise of antibiotic resistance (ABR) as a significant global concern.[51] (Figure 3).

Antibiotic resistance (ABR) presents a significant challenge not just within the food sector but also in public health. Antimicrobial resistance (AMR) has garnered global attention, leading the World Health Organization (WHO) to establish the Global Action Plan on antibacterial and antifungal resistance. This plan aims to advocate

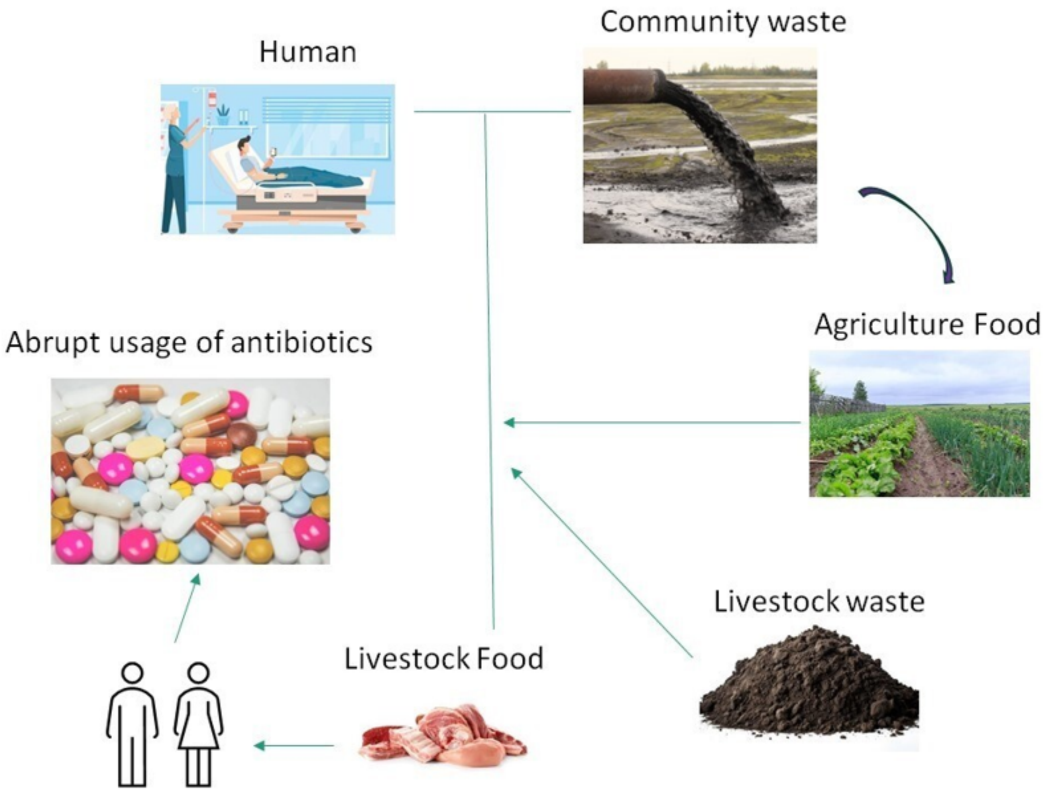

Figure 3: Sources of AMR

responsible antibiotic usage and develop strategies to mitigate antibiotic consumption. It underscores various health risks, particularly the escalating difficulty in treating common bacterial infections like, urinary tract infections, foodborne illnesses, pneumonia, bloodstream infections sexually transmitted diseases, and tuberculosis due to microbial resistance to usual antibiotics. As resistance mechanisms progress, microorganisms develop the ability to withstand existing antibiotic treatments. Multidrug resistance (MDR) emerges as another consequence of ABR, wherein bacteria develop resistance to multiple antibiotics concurrently. Multidrug-resistant (MDR) organisms, including, *Eschirichia coli, Enterococcus faecalis, Acinatobactor baumannii, Pseudomonas aeruginosa, Staphylococcus aureus, Streptococcus pneumoniae, Enterococcus faecium*, and *Klebsiella pneumoniae* represent a significant threat to public health, with their prevalence on the rise. Infections caused by multidrug-resistant (MDR) bacteria often result in more severe illness and higher mortality rates, adding strain to healthcare systems. Irresponsible antibiotic use, whether in broad or specific treatments, can negatively impact both the pharmacological and economic dimensions of public health systems.[52] (Figure 3).

Many nations lack effective surveillance systems to track antibiotic usage adequately. Establishing a regulatory framework at both local and international levels is essential for evaluating antibiotic use's risks and benefits. This framework should be comprehensive, supported by standards, guidelines, and recommendations, to regulate antibiotic usage across the food chain.[53] Despite advancements in analytical techniques for identifying foodborne microbes, traditional food safety practices mainly test finished products, identifying hazards late in processing. This approach often overlooks non-microbiological issues like environmental factors and antibiotic contamination. Chemical analysis of final products remains the primary method for detecting antibiotics in food. Mass spectrometry (MS) and High-performance Liquid Chromatography (HPLC) are commonly used due to their high sensitivity, allowing for trace-level detection of antibiotic residues. However, current methods focus on final product analysis, neglecting the monitoring of antibiotic residues during processing. Continuous monitoring throughout processing is vital for quality assurance in the food industry, especially given rising concerns about Antibiotic Resistance (ABR) and potential antibiotic molecule alterations during processing.[51,53] Antibiotic infections can cause significant adverse effects in four key areas: animal health,[54] environmental damage,[55] transformation processes[7] and consumer health.[44] Antibiotic residues might trigger allergic reactions, presenting as thrombocytopenia, skin rashes, acute interstitial nephritis, erythema multiforme, serum sickness hemolytic anemia, vasculitis, toxic epidermal necrolysis, and Stevens–Johnson syndrome. Such allergic reactions have been reported in individuals consuming contaminated meat and milk. Additionally, antibiotic residues in food are linked to carcinogenesis, liver toxicity, mutagenesis, teratogenicity, and reproductive disorders. These residues can also disrupt the gut microbiome, causing dysbiosis, which may lead to obesity, compromised intestinal barrier function, and increased susceptibility to food allergies.[56] Examining food security and sustainability through microbiology underscores the importance of microbial diversity in creating resilient and efficient global food systems. Microorganisms are essential for improving soil health, increasing crop yields, and preserving food through fermentation, thus supporting sustainable agriculture. Challenges like antimicrobial resistance, foodborne illnesses, and food wastage necessitate efficient utilization of microbial diversity. Exploring microbial-driven solutions, biopreservation methods, and innovative risk mitigation strategies is crucial. Microbiology offers promising avenues to address these challenges.

9. Conclusion

From the above we can conclude that through interdisciplinary cooperation and informed policy frameworks, we can fully harness microbial diversity to develop robust and inclusive food systems. This approach can enhance agricultural resilience, improve food security, and promote sustainability, benefiting communities worldwide. Prioritizing research, education, and investment in microbiology-centric methods is crucial for enhancing food security and sustainability. Integrating microbial perspectives into agriculture, food production, and waste management will help navigate environmental and economic complexities, ensuring access to safe, nutritious, and sustainable food. Recognizing microbiology's essential role is vital for achieving food security and sustainability for future generations.

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11. Conflict of Interest

None.

References

1. Boqvist S, Söderqvist K, Vågsholm I. Food safety challenges and One Health within Europe. *Acta Vet Scand*. 2018;60:1–13.
2. Marco ML, Heeney D, Binda S, Cifelli CJ, Cotter PD, Foligné B, et al. Health benefits of fermented foods: microbiota and beyond. *Curr Opin Biotechnol*. 2017;44:94–102.
3. Muteeb G, Rehman MT, Shahwan M, Aatif M. Origin of antibiotics and antibiotic resistance, and their impacts on drug development: A narrative review. *Pharmaceuticals (Basel)*. 2023;16(11):1615.
4. Golden DBK, Wang J, Waserman S, Akin C, Campbell RL, Ellis AK, et al. Anaphylaxis: A 2023 practice parameter update. *Ann Allergy Asthma Immunol*. 2024;132(2):124–76.
5. DeGraaff MA, Hornslein N, Throop HL, Kardol P, Diepen LTV. Effects of agricultural intensification on soil biodiversity and implications for ecosystem functioning: a meta-analysis. *Adv Agronomy*. 2019;155:1–44.
6. Fang K, Jin X, Hong SH. Probiotic Escherichia coli inhibits biofilm formation of pathogenic E. coli via extracellular activity of DegP. *Sci Rep*. 2018;8(1):4939.
7. Nivelle E, Verzeaux J, Habbib H, Kuzyakov Y, Decocq G, Roger D, et al. Functional response of soil microbial communities to tillage, cover crops and nitrogen fertilization. *Appl Soil Ecol*. 2016;108:147–55.
8. Silveira RF, Roque-Borda CA, Vicente EF. Antimicrobial peptides as a feed additive alternative to animal production, food safety and public health implications: An overview. *Anim Nutr*. 2021;7(3):896–904.
9. Nji E, Kazibwe J, Hambridge T, Joko CA, Larbi AA, Damptey LAO, et al. High prevalence of antibiotic resistance in commensal Escherichia coli from healthy human sources in community settings. *Sci Rep*. 2021;11(1):3372.
10. Lv X, Wu Y, Gong M, Deng J, Gu Y, Liu Y, et al. Synthetic biology for future food: research progress and future directions. *Future Foods*. 2021;3:100025.
11. DeMandal S, Jeon J. Phyllosphere Microbiome in Plant Health and Disease. *Plants*. 2023;12(19):3481.
12. Busby PE, Soman C, Wagner MR, Friesen ML, Kremer J, Bennett A, et al. Research priorities for harnessing plant microbiomes in sustainable agriculture. *PLoS Biol*. 2017;15(3):e2001793.
13. Nelson DW, Moore JE, Rao JR. Antimicrobial resistance (AMR): significance to food quality and safety. *Food Qual Saf*. 2019;3(1):15–22.
14. Legrand F, Picot A, Cobo-Díaz JF, Carof M, Chen W, Floch GL. Effect of tillage and static abiotic soil properties on microbial diversity. *Appl Soil Ecol*. 2018;132:135–45.
15. Jaroni D, Litt PK, Bule P, Rumbaugh K. Effectiveness of bacteriophages against biofilm-forming Shiga-toxigenic Escherichia coli in vitro and on food-contact surfaces. *Foods*. 2023;12(14):2787.
16. Samutela MT, Kwenda G, Simulundu E, Nkhoma P, Higashi H, Frey A, et al. Pigs as a potential source of emerging livestock-associated Staphylococcus aureus in Africa: a systematic review. *Int J Infect Dis*. 2021;109:38–49.
17. Hughes A, Roe E, Hocknell S. Food supply chains and the antimicrobial resistance challenge: On the framing, accomplishments, and limitations of corporate responsibility. *Environ Plan Econ Space*. 2021;53(6):1373–90.
18. Yefet E, Bar L, Izhaki I, Iskander R, Massalha M, Younis JS, et al. Effects of probiotics on glycemic control and metabolic parameters in gestational diabetes mellitus: systematic review and meta-analysis. *Nutrients*. 2023;15(7):1633.
19. Patel J, Sharma M, Millner P, Calaway T, Singh M. Inactivation of Escherichia coli O157: H7 attached to spinach harvester blade using bacteriophage. *Foodborne Pathog Dis*. 2011;8(4):541–6.
20. Krishnan SV, Nampoothiri KM, Suresh A, Linh NT, Balakumaran PA, Pócsi I, et al. Fusarium biocontrol: antagonism and mycotoxin elimination by lactic acid bacteria. *Front Microbiol*. 2024;14:1260166.

21. Sans AF. Guía para la prevención del fraude en la industria agroalimentaria; 2018. Available from: http://coli.usal.es/web/Guias/pdf/Guia_Prevencion_Fraude_Indus_Agroali.pdf.
22. Maberry T. A look back at 2015 food recalls; 2016. Available from: https://www.food-safety.com/articles/4289-a-look-back-at-2015-food-recalls.
23. Ganguly S. Basic principles for effective food preservation: A review. *Int J Pure App Biosci*. 2013;1(6):84–5.
24. Solecki R, Kortenkamp A, Bergman Å, Chahoud I, Degen GH, Dietrich D, et al. Scientific principles for the identification of endocrine-disrupting chemicals: a consensus statement. *Arch Toxicol*. 2017;91:1001–6.
25. Bintsis T, Papademas P. The Application of Protective Cultures in Cheese: A review. *Fermentation*. 2024;10(3):117.
26. Founou LL, Founou RC, Essack SY. Antibiotic resistance in the food chain: a developing country-perspective. *Front Microbiol*. 2016;7:232834.
27. Rega M, Andriani L, Poeta A, Casadio C, Diegoli G, Bonardi S, et al. Transmission of β-lactamases in the pork food chain: A public health concern. *One Health*. 2023;17(1):100632.
28. Sauvé S. Toxicology, environmental chemistry, ecotoxicology, and One Health: definitions and paths for future research. *Front Environ Sci*. 2024;12:1303705.
29. Mokoena MP. Lactic acid bacteria and their bacteriocins: classification, biosynthesis and applications against uropathogens: a mini-review. *Molecules*. 2017;22(8):1255.
30. Pinto L, Tapia-Rodríguez MR, Baruzzi F, Ayala-Zavala JF. Plant antimicrobials for food quality and safety: Recent views and future challenges. *Foods*. 2023;12(12):2315.
31. Cornelius AJ, Carr SD, Bakker SN, Haysom IW, Dyet KH. Antimicrobial Resistance in Selected Bacteria from Food Animals in New Zealand 2018-2022. *J Food Prot*. 2024;87(4):100245.
32. He J, Evans NM, Liu H, Shao S. A review of research on plant-based meat alternatives: Driving forces, history, manufacturing, and consumer attitudes. *Compr Rev Food Sci Food Saf*. 2020;19(5):2639–56.
33. Food and Agriculture Organization. Manual on development and use of FAO and WHO specifications for pesticides, -third revision. plant production and protection paper. Rome: World Health Organization and FAO; 2016.
34. Păucean A, Șerban LR, Chiș MS, Mureșan V, Pușcaș A, Man SM, et al. Nutritional composition, in vitro carbohydrates digestibility, textural and sensory characteristics of bread as affected by ancient wheat flour type and sourdough fermentation time. *Food Chem X*. 2024;22:101298.
35. Esteve-Redondo P, Heras-Mozos R, Simó-Ramírez E, López-Carballo G, López-De-Dicastillo C, Gavara R, et al. Innovative Systems for the Delivery of Naturally Occurring Antimicrobial Volatiles in Active Food-Packaging Technologies for Fresh and Minimally Processed Produce: Stimuli-Responsive Materials. *Foods*. 2024;13(6):856.
36. Okocha RC, Olatoye IO, Adedeji OB. Food safety impacts of antimicrobial use and their residues in aquaculture. *Public Health Rev*. 2018;39:1–21.
37. Tuo Y, Song X, Song Y, Liu W, Tang Y, Gao Y, et al. Screening probiotics from Lactobacillus strains according to their abilities to inhibit pathogen adhesion and induction of pro-inflammatory cytokine IL-8. *J Dairy Sci*. 2018;101(6):4822–9.
38. García-Bayona L, Guo MS, Laub MT. Contact-dependent killing by Caulobacter crescentus via cell surface-associated, glycine zipper proteins. *eLife*. 2017;6:e24869.
39. Kim J, Adhikari K. Current trends in kombucha: Marketing perspectives and the need for improved sensory research. *Beverages*. 2020;6(1):15.
40. Greenberg M, Kuo D, Jankowsky E, Long L, Hager C, Bandi K, et al. Small-molecule AgrA inhibitors F12 and F19 act as antivirulence agents against Gram-positive pathogens. *Sci Rep*. 2018;8(1):14578.
41. Ghosh B, Sukumar G, Ghosh AR. Purification and characterization of pediocin from probiotic Pediococcus pentosaceus GS4, MTCC 12683. *Folia Microbiol*. 2019;64:765–78.
42. Bleriot I, Pacios O, Blasco L, Fernández-García L, López M, Ortiz-Cartagena C, et al. Improving phage therapy by evasion of phage resistance mechanisms. *JAC Antimicrob Resist*. 2024;6(1):dlae017.
43. Ji J, Yang H. Using probiotics as supplementation for Helicobacter pylori antibiotic therapy. *Int J Mol Sci*. 2020;21(3):1136.
44. Mainardi PH, Bidoia ED. Food safety management: preventive strategies and control of pathogenic microorganisms in food. *Eur J Biol Res*. 2024;14(1):13–32.
45. Hassani S, Moosavy MH, Gharajalar SN, Khatibi SA, Hajibemani A, Barabadi Z. High prevalence of antibiotic resistance in pathogenic foodborne bacteria isolated from bovine milk. *Sci Rep*. 2022;12(1):3878.
46. Narayan OP, Kumar P, Yadav B, Dua M, Johri AK. Sulfur nutrition and its role in plant growth and development. *Plant Signal Behav*. 2023;18(1):2030082.
47. Oppedisano F, DeFazio R, Gugliandolo E, Crupi R, Palma E, Raza SHA, et al. Mediterranean Plants with Antimicrobial Activity against Staphylococcus aureus, a Meta-Analysis for Green Veterinary Pharmacology Applications. *Microorganisms*. 2023;11(9):2264.
48. Wu-Wu JWF, Guadamuz-Mayorga C, Oviedo-Cerdas D, Zamora WJ. Antibiotic resistance and food safety: perspectives on new technologies and molecules for microbial control in the food industry. *Antibiotics (Basel)*. 2023;12(3):550.
49. Feng J, Liu YR, Eldridge D, Huang Q, Tan W, Delgado-Baquerizo M. Geologically younger ecosystems are more dependent on soil biodiversity for supporting function. *Nat Commun*. 2024;15(1):4141.
50. Nair MS, Amalaradjou MA, Venkitanarayanan K. Antivirulence properties of probiotics in combating microbial pathogenesis. *Adv Appl Microbiol*. 2017;98:1–2.
51. Moebus S, Boedeker W. Frequency and trends of hospital treated pesticide poisonings in Germany 2000–2014. *Ger Med Sci*. 2017;15:13.
52. Bacanlı M, Başaran N. Importance of antibiotic residues in animal food. *Food Chem Toxicol*. 2019;125:462–6.
53. Chen J, Ying GG, Deng WJ. Antibiotic residues in food: extraction, analysis, and human health concerns. *J Agric Food Chem*. 2019;67(27):7569–86.
54. EFSA. Monitoring data on pesticide residues in food: results on organic versus conventionally produced food. *EFSA J*. 2018;15(4):1397.
55. Gautam R. Climate Change and Security with Reference to Food Security: A Systematic Literature Review. *Glob J Enterprise Inf Syst*. 2023;15(4):57–69.
56. Ben Y, Hu M, Zhong F, Du E, Li Y, Zhang H, et al. Human daily dietary intakes of antibiotic residues: Dominant sources and health risks. *Environ Res*. 2022;212(Pt C):113387.

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