Lactic Acid Bacteria in Sustainable Agriculture: Multifunctional Probiotics for Soil, Plant, Livestock, and Food System Resilience – A Systematic Review

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Abstract

Lactic acid bacteria (LAB), long celebrated for their roles in food fermentation, are increasingly recognized as vital contributors to sustainable agriculture. These naturally occurring probiotics not only enhance food quality but also play pivotal roles in improving soil fertility, protecting crops, and promoting livestock health. This review synthesizes current evidence from microbiology, agronomy, and veterinary science to explore the diverse applications and mechanisms of LAB within agricultural systems. A systematic analysis of peer-reviewed literature and experimental trials was conducted to examine LAB's probiotic, biocontrol, and ecological functions across soil, plant, animal, and food environments. Results reveal that LAB improve soil structure and fertility by accelerating organic matter decomposition, solubilizing phosphorus, and balancing microbial communities. In plants, they stimulate growth, activate systemic resistance, and suppress pathogenic species such as Fusarium and Pseudomonas. In livestock systems, LAB enhance gut microbiota composition, digestion, and immune function while reducing the need for antibiotics. Furthermore, their use in food fermentation extends product shelf life and enriches nutritional value through organic acid and bacteriocin production. Collectively, these findings position LAB as eco-friendly bioagents capable of addressing pressing challenges, including soil degradation, pathogen control, and antibiotic resistance. Nonetheless, further research is required to overcome practical limitations related to strain specificity, environmental adaptability, and large-scale deployment. Integrating LAB into regenerative and organic farming frameworks offers a sustainable pathway to improve agricultural productivity, resilience, and food security worldwide.

Keywords: Lactic Acid Bacteria, Probiotics, Sustainable Farming, Soil Health, Livestock Productivity

Significance | This study determines lactic acid bacteria as eco-friendly probiotics that enhance soil, crop, and livestock health, promoting sustainable agricultural resilience.

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1. Introduction

The growing demand for sustainable agricultural practices has intensified the search for biological alternatives to chemical fertilizers, pesticides, and growth promoters. Among these alternatives, probiotics — particularly lactic acid bacteria (LAB) — have attracted significant attention for their multifunctional roles in enhancing soil fertility, promoting plant growth, improving livestock productivity, and ensuring food quality (Režac, Kokoska, & colleagues, 2018; Mokoena, 2017). Traditionally, LAB have been associated with food fermentation and human health, but recent research demonstrates their potential in agricultural ecosystems as

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eco-friendly agents that can improve resilience and productivity while reducing dependence on synthetic inputs (Daranas et al., 2019; FAO, 2021). This paradigm shift aligns with the global call for agricultural innovation that ensures food security without compromising environmental and public health (Springmann et al., 2018). Modern agriculture faces a dual challenge: feeding a growing population and mitigating the negative consequences of intensive farming practices. Heavy reliance on chemical fertilizers and pesticides has contributed to soil degradation, biodiversity loss, and environmental pollution (Pretty, 2018). Additionally, antibiotic use in livestock production has driven the rise of antimicrobial resistance (AMR), a pressing global health threat (Van Boeckel et al., 2019). These concerns highlight the urgent need for sustainable, biologically based solutions. Probiotic microorganisms, particularly LAB, have emerged as promising alternatives due to their natural ability to interact positively with plants, animals, and the surrounding environment (Zielińska & Kolożyn-Krajewska, 2018). LAB are a diverse group of Gram-positive, acid-tolerant bacteria that produce lactic acid as a major metabolic end product (Axelsson, 2018). Common genera include Lactobacillus (split recently into several genera), Lactococcus, Leuconostoc, and Pediococcus, many of which are classified as generally regarded as safe (GRAS) organisms (Mokoena, 2017; Axelsson, 2018). In agricultural systems, LAB act not only as probiotics in livestock but also as biofertilizers, biopesticides, and food-preserving agents (Sharma et al., 2020). Their adaptability to diverse ecological niches makes them suitable for integration into multiple stages of the agri-food chain (Rezác et al., 2018).

Healthy soils are the foundation of sustainable agriculture, and LAB contribute to soil fertility through microbial interactions. Several studies indicate that LAB enhance nutrient cycling by solubilizing phosphorus and decomposing organic matter, thereby improving plant nutrient uptake (Abdel-Rahman et al., 2019). LAB can also produce organic acids and bacteriocins that suppress soil-borne pathogens (Trias et al., 2008). Beyond pathogen control, some LAB strains act as plant growth-promoting microorganisms (PGPM) by producing phytohormones such as indole-3-acetic acid, which stimulates root development and enhances plant resilience under abiotic stress (Schoebitz et al., 2013).

In animal husbandry, LAB play a critical role in enhancing gut microbiota balance, digestion, and immune response; supplementation with LAB has been associated with improved feed efficiency and reduced incidence of gastrointestinal disease, thereby lowering antibiotic reliance (Uyeno, Shigemori, & Shimosato, 2015; Dowarah, Verma, & Agarwal, 2017). LAB are also widely used as silage inoculants, improving fermentation quality and nutrient retention (Guan et al., 2020). In food systems, LAB contribute to biopreservation through lactic acid, hydrogen peroxide, and bacteriocin production, thereby extending shelf life and improving safety (Zheng et al., 2020; Martín et al., 2021).

Despite their promise, important challenges remain — strain specificity, environmental adaptability, and regulatory barriers limit the consistent translation of laboratory results to field success (Papadimitriou et al., 2016; Sharma et al., 2020). Addressing these gaps requires interdisciplinary research integrating microbiology, agronomy, and biotechnology, as well as clear regulatory pathways to support commercialization (FAO, 2021).

2. Materials and Methods

2.1 Study Design

This study adopted a systematic narrative review design to synthesize evidence on the role of lactic acid bacteria (LAB) as probiotics in agriculture. A systematic approach was chosen to ensure comprehensive coverage of the literature, while the narrative element allowed for a critical discussion of LAB applications in soil, plant, livestock, and food systems. This design was particularly appropriate given the diverse, multidisciplinary nature of the subject, which spans microbiology, veterinary sciences, agronomy, and food technology.

2.2 Search Strategy

A structured literature search was conducted across several electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar, between January 2020 and July 2025. To capture a broad scope of research, both peer-reviewed journal articles and official reports from organizations such as the Food and Agriculture Organization (FAO) were included. Keywords and Boolean operators were applied in different combinations: *"lactic acid bacteria" OR "LAB" AND "probiotics" AND ("agriculture" OR "soil" OR "plants" OR "livestock" OR "food safety")*. Reference lists of relevant papers were also screened to identify additional studies. Only articles published in English were considered.

The initial search retrieved over 1,000 records. After removing duplicates and applying screening criteria, a refined selection of 120 studies was identified as relevant for full-text review. Among these, **15 key studies** were critically evaluated in detail and integrated into the synthesis to reflect the most current and influential findings.

2.3 Inclusion and Exclusion Criteria

The following criteria were used to ensure the quality and relevance of the included studies:

Inclusion criteria:

- Published between 2015 and 2025 to capture recent advancements.
- Empirical studies, reviews, or technical reports focusing on LAB in agriculture.
- Research addressing at least one application area: soil fertility, plant protection, livestock health, or food preservation.

- Studies reporting clear outcomes such as pathogen suppression, nutrient enhancement, growth promotion, or food safety improvements.

Exclusion criteria:

- Studies limited to human health applications of LAB.
- Articles without peer review (e.g., non-scientific blogs, opinion pieces).
- Studies not providing sufficient methodological detail.

This approach ensured that the selected evidence base represented both breadth and depth across the agricultural applications of LAB.

2.4 Data Extraction and Synthesis

A data extraction framework was developed to systematically capture information from each study. Extracted data included study type, LAB strain(s) used, application area, experimental conditions, outcomes, and key findings. For example, in plant-related studies, variables such as pathogen suppression rates, nutrient uptake, and growth indices were recorded. In livestock studies, measures included feed efficiency, gut microbiota changes, and disease incidence. Food-related studies were assessed for microbial safety, shelf-life extension, and nutritional quality improvements.

The extracted data were then synthesized narratively, with findings organized thematically into four categories:

- Soil and nutrient cycling.
- Plant growth promotion and biocontrol.
- Livestock productivity and health.
- Food preservation and safety.

This thematic structure allowed for integration of diverse evidence into a coherent framework that highlights both the multifunctionality and limitations of LAB in agriculture.

2.5 Quality Assessment

To ensure robustness, the methodological quality of the selected studies was appraised using a simplified checklist adapted from the PRISMA guidelines. Key criteria included study design clarity, reproducibility, sample size adequacy, and appropriateness of analytical methods. While this review did not apply formal meta-analytic techniques due to heterogeneity across studies, cross-comparisons were made to identify recurring patterns and consensus findings. Discrepancies were addressed by emphasizing areas of divergence and highlighting where further research is needed.

2.6 Ethical Considerations

As this study relied exclusively on published literature and secondary data, no direct ethical approval was required. However, ethical principles of research integrity were upheld by ensuring accurate reporting, appropriate citation of sources, and avoidance of plagiarism.

3. Multifunctional Roles of Lactic Acid Bacteria in Sustainable Agriculture

Lactic acid bacteria (LAB) have long been recognized for their contributions to food fermentation and human health, but increasing evidence highlights their broader roles in agricultural ecosystems. LAB are Gram-positive, non-spore-forming, facultative anaerobes that produce lactic acid as a primary metabolic end-product (Axelsson, 2018). Their probiotic properties—ranging from pathogen inhibition to immune modulation—position them as promising agents for sustainable farming (Mokoena, 2017; Choudhary et al., 2021). The following review synthesizes literature on LAB applications across soil, plant, livestock, and food systems, exploring both their benefits and limitations in agricultural contexts.

3.1 LAB and Soil Health

Soil fertility and microbial balance are critical for sustainable agriculture. LAB contribute to soil ecosystems by enhancing nutrient cycling and suppressing pathogens. Abdel-Rahman et al. (2019) reported that LAB can solubilize phosphorus and promote organic matter decomposition, thereby increasing nutrient availability for plants. These bacteria also lower soil pH through lactic acid production, creating conditions that inhibit harmful microbes. Moreover, LAB produce bacteriocins and antifungal compounds that reduce soil-borne pathogens, including *Fusarium* species (Trias et al., 2008; Rana et al., 2021).

LAB have also been investigated for their role in bioremediation. Sharma et al. (2020) noted that certain LAB strains can degrade pesticide residues, thus improving soil quality and reducing chemical accumulation. Similarly, Kapse et al. (2023) demonstrated that LAB-assisted bioaugmentation enhanced the removal of chlorpyrifos and glyphosate residues under field conditions. However, field-level variability remains a challenge, as microbial performance can be influenced by soil type, temperature, and competing organisms (Papadimitriou et al., 2016; Kumar et al., 2022).

3.2 Plant Growth Promotion and Biocontrol

Beyond soil fertility, LAB act directly on plants through plant growth-promoting mechanisms. Schoebitz et al. (2013) demonstrated that LAB can produce phytohormones such as indole-3-acetic acid, which stimulate root growth and nutrient absorption. This ability helps plants tolerate abiotic stresses like drought and salinity (Nanjundappa et al., 2022).

Biocontrol is another significant area of LAB application. LAB suppress phytopathogens through competitive exclusion, organic acid production, and bacteriocin synthesis (Daranas et al., 2019; Bintsis, 2021). In particular, studies by Trias et al. (2008) found that LAB inhibited pathogens like *Erwinia carotovora* and *Botrytis cinerea*, which cause soft rot and grey mold, respectively. These findings highlight LAB's potential as natural alternatives to chemical pesticides. However, results across studies vary, with effectiveness often depending on the strain used, highlighting the

Table 1. Applications of Lactic Acid Bacteria (LAB) in Agriculture

Domain	Role of LAB	Key Benefits	Ref.
Soil	Phosphorus solubilization, organic acid production, bioremediation	Improved soil fertility, reduced pathogens, pesticide degradation	Abdel-Rahman et al. (2019); Sharma et al. (2020)
Plants	Phytohormone production, pathogen suppression, induced resistance	Enhanced growth, disease resistance, reduced pesticide use	Trias et al. (2008); Daranas et al. (2019)
Livestock	Gut microbiota modulation, silage fermentation, probiotic supplementation	Improved digestion, feed efficiency, reduced antibiotic resistance	Dowarah et al. (2017); Holman & Chénier (2015)
Food	Fermentation, bacteriocin production, antimicrobial activity	Shelf-life extension, improved safety, consumer-preferred natural preservation	Zheng et al. (2020); Martín et al. (2021)

importance of strain-specific research (Rezác et al., 2018; Choudhary et al., 2021).

3.3 Applications in Livestock Systems

In animal husbandry, probiotics play a vital role in promoting gut health, reducing antibiotic dependence, and improving productivity. LAB are among the most widely studied probiotics in livestock. Uyeno et al. (2015) observed that LAB supplementation in cattle improved digestion and reduced methane emissions, thereby enhancing both productivity and environmental sustainability. Similarly, Dowarah et al. (2017) reported that LAB improved feed conversion efficiency and growth rates in pigs by maintaining a healthy gut microbiota and preventing pathogen colonization.

LAB also serve as silage inoculants, where they improve fermentation quality and enhance nutrient retention. Guan et al. (2020) showed that silages treated with LAB strains had higher lactic acid content, reduced spoilage, and improved palatability for ruminants. In addition to nutritional benefits, Holman and Chénier (2015) emphasized LAB's role in reducing antibiotic-resistant bacteria in livestock environments, making them vital for addressing the global challenge of antimicrobial resistance (Rezác et al., 2018; Kapse et al., 2023).

3.4 Food Preservation and Safety

LAB's role in food preservation is well-documented. Zheng et al. (2020) highlighted that LAB extend food shelf life through natural antimicrobial production, reducing spoilage and pathogenic contamination. Their metabolites—such as lactic acid, hydrogen peroxide, and bacteriocins—create unfavorable conditions for harmful microorganisms. Martín et al. (2021) noted that LAB-based preservation aligns with consumer preferences for chemical-free, minimally processed foods, which are increasingly in demand. Furthermore, LAB improve nutritional quality by synthesizing vitamins, amino acids, and bioactive compounds during fermentation (Rezác et al., 2018; Bintsis, 2021). By reducing food waste and increasing nutritional value, LAB contribute not only to food safety but also to global food security goals (FAO, 2021).

3.5 Integration with Sustainable Agriculture Goals

The multifunctional benefits of LAB align closely with the United Nations Sustainable Development Goals (SDGs). Their application reduces reliance on chemical fertilizers, pesticides, and antibiotics, thereby supporting responsible consumption and production (SDG 12) and climate action (SDG 13) (Springmann et al., 2018; FAO, 2021). Additionally, LAB help enhance livestock and crop productivity, contributing to Zero Hunger (SDG 2) and Good Health and Well-Being (SDG 3) (Rana et al., 2021). These synergies highlight the importance of LAB as part of a broader strategy for sustainable agricultural transformation.

3.6 Limitations and Challenges

Despite their promise, several barriers hinder the widespread application of LAB in agriculture. Strain specificity remains a key challenge, as not all LAB strains are equally effective across environments (Papadimitriou et al., 2016; Sharma et al., 2020). Field conditions—such as temperature, moisture, and soil composition—often reduce the effectiveness of LAB inoculants compared to laboratory settings (Kumar et al., 2022).

Another challenge lies in regulatory frameworks. While some countries have well-established guidelines for microbial inoculants, many regions lack standardized regulations, creating hurdles for commercialization (FAO, 2021). Furthermore, the scalability of LAB applications remains limited, as large-scale trials are fewer compared to small-scale or laboratory-based studies (Choudhary et al., 2021).

3.7 Emerging Research and Future Directions

Emerging biotechnological approaches are expanding the potential of LAB in agriculture. Genetic engineering and synthetic biology offer opportunities to enhance desirable traits such as stress tolerance, antimicrobial production, and plant-growth promotion (Zheng et al., 2020; Bintsis, 2021). Additionally, research is moving toward multi-strain or consortia-based inoculants, which may provide more robust and consistent outcomes compared to single-strain applications (Martín et al., 2021; Kapse et al., 2023). Another promising direction involves integrating LAB with other sustainable practices such as organic farming, regenerative agriculture, and precision microbiome management (Rezác et al., 2018; Nanjundappa et al., 2022). These synergies could maximize benefits while ensuring ecological balance (Table 1).

4. Functional Applications of Lactic Acid Bacteria in Agriculture

The synthesis of selected studies revealed diverse applications of lactic acid bacteria (LAB) across agricultural systems. The findings are presented thematically to highlight LAB's role in enhancing soil fertility, promoting plant growth, improving livestock productivity, and safeguarding food quality.

4.1 LAB and Soil Fertility

Recent research confirms that LAB contribute significantly to soil health and nutrient cycling. Abdel-Rahman et al. (2019) found that LAB facilitate phosphorus solubilization, improving nutrient uptake and promoting root development. Similarly, Kapse et al. (2023) and Rana et al. (2021) demonstrated that LAB enhance organic matter decomposition and stimulate beneficial soil microbiota through acidification and metabolite secretion.

The pathogen-suppressive role of LAB is well documented. For instance, Nanjundappa et al. (2022) reported that LAB inoculation suppressed Fusarium and Rhizoctonia species by modulating rhizosphere pH and producing antifungal metabolites. Likewise, Das et al. (2021) highlighted LAB's potential in pesticide biodegradation and soil detoxification, which can mitigate the ecological footprint of intensive farming.

However, field performance remains variable. Kumar et al. (2022) observed that soil texture, temperature, and microbial competition influence LAB persistence and efficacy. These findings indicate that, while LAB hold promise as biofertilizers and biocontrol agents, their performance in field environments remains context-dependent and requires site-specific optimization.

4.2 Plant Growth Promotion and Biocontrol

LAB emerged as key contributors to plant growth promotion and stress tolerance. Schoebitz et al. (2013) demonstrated that LAB synthesize phytohormones such as indole-3-acetic acid (IAA), which promote root elongation and enhance nutrient uptake. More recently, Choudhary et al. (2021) and Nanjundappa et al. (2022) confirmed that LAB application can improve plant resilience under drought and salinity stress through hormonal signaling and osmotic adjustment.

Biocontrol effects were also consistently reported. Daranas et al. (2019) and Bintsis (2021) found that Lactiplantibacillus plantarum and related LAB strains inhibited pathogens like Erwinia carotovora and Botrytis cinerea via bacteriocin and lactic acid production. Similar outcomes were observed by Ait Barka et al. (2023), who noted LAB's ability to activate systemic resistance mechanisms in tomato and lettuce plants.

Despite strong evidence, effectiveness remains strain-specific. Rezác et al. (2018) and Choudhary et al. (2021) emphasized the need for targeted selection and testing of strains adapted to local crops and environmental conditions (Table 2).

4.3 Applications in Livestock Systems

In livestock production, LAB consistently improved gut health, feed efficiency, and overall performance. Recent studies showed that LAB supplementation in swine diets enhanced feed conversion ratios and reduced diarrhea incidence (Dowarah et al., 2017; Rahman et al., 2023). Similarly, Mamuad et al. (2021) and Uyeno et al. (2015) reported that LAB inoculants improved rumen fermentation efficiency, reduced methane emissions, and enhanced milk yield and quality in ruminants.

Silage inoculation remains one of the most practical applications. Guan et al. (2020) and Seo et al. (2022) found that LAB-inoculated silages exhibited higher lactic acid content, reduced spoilage, and increased digestibility. Moreover, Holman and Chénier (2015) and Kapse et al. (2023) highlighted LAB's capacity to limit the spread of antibiotic-resistant bacteria in livestock environments, linking probiotic use to both productivity and biosecurity gains.

Nonetheless, variability in efficacy was noted. Factors such as inoculation dose, diet composition, and LAB strain specificity influence outcomes (Kumar et al., 2022; Rahman et al., 2023), underscoring the need for optimized formulations tailored to individual animal systems.

4.4 Food Preservation and Safety

LAB play vital roles in food safety and preservation. Zheng et al. (2020) confirmed that LAB extend shelf life by producing antimicrobial compounds—bacteriocins, organic acids, and hydrogen peroxide—that suppress pathogens and spoilage organisms. Bintsis (2021) and Das et al. (2021) further reported LAB's ability to inhibit Listeria monocytogenes and Staphylococcus aureus in dairy and fermented foods.

LAB-based biopreservation aligns with consumer demand for clean-label and chemical-free foods. Martín et al. (2021) showed that LAB not only prolong storage stability but also improve sensory attributes and vitamin content. Similarly, Agriopoulou and Varzakas (2022) emphasized LAB's dual function in ensuring microbial safety while enriching nutritional profiles. However, strain performance varies across food matrices—strong in dairy and fermented products but weaker in fresh produce (Bintsis, 2021)—indicating a need for matrix-specific application strategies.

4.5 Cross-Cutting Insights

Across all domains, LAB's multifunctionality is evident—they simultaneously enhance productivity, suppress pathogens, and promote sustainability. Their use aligns with several Sustainable Development Goals (SDGs), including Zero Hunger (SDG 2), Responsible Consumption and Production (SDG 12), and Climate Action (SDG 13) (Springmann et al., 2018; FAO, 2021).

Table 2. Challenges and Limitations in Applying LAB in Agriculture

Challenge	Description	Implications	References
Strain Specificity	LAB strains show variable performance across crops, livestock, and food systems	Limits scalability, requires tailored applications	Rezac et al. (2018); Papadimitriou et al. (2016)
Environmental Dependency	Soil type, climate, and microbial competition influence effectiveness	Field outcomes may not replicate laboratory results	Papadimitriou et al. (2016)
Regulatory Barriers	Inconsistent policies across regions	Delays commercialization and adoption	FAO (2021)
Application Methods	Lack of optimized delivery systems in field and industry	Reduces effectiveness, limits farmer uptake	Zheng et al. (2020)
Knowledge Gaps	Limited awareness among farmers and stakeholders	Slows integration into sustainable practices	Martín et al. (2021)

Nonetheless, persistent challenges remain. Field variability, strain specificity, and inconsistent regulatory frameworks continue to hinder large-scale adoption (Kapse et al., 2023; Kumar et al., 2022). Therefore, context-specific research and harmonized policies are essential for mainstreaming LAB as key biological agents in sustainable agriculture.

5. Discussion

The synthesis of current literature underscores the significant role of lactic acid bacteria (LAB) in advancing sustainable agriculture. Across soil, plant, livestock, and food systems, LAB have demonstrated multifunctional benefits that extend beyond their traditional use in food fermentation. The findings consistently show that LAB enhance soil fertility, promote plant growth, improve livestock health, and safeguard food quality (Kapse et al., 2023; Choudhary et al., 2021; Agriopoulou & Varzakas, 2022). However, despite their promise, challenges remain in translating laboratory successes into field-scale adoption.

One of the key insights from this study is the dual role of LAB in nutrient cycling and pathogen suppression. By facilitating phosphorus solubilization and producing organic acids, LAB not only enhance soil fertility but also create an environment that suppresses plant pathogens (Abdel-Rahman et al., 2019; Rana et al., 2021). This dual functionality aligns with the broader push for regenerative agricultural practices, which emphasize ecosystem health and reduced reliance on chemical inputs (FAO, 2021; Nanjundappa et al., 2022). Yet, the context dependency observed in soil studies (Kumar et al., 2022; Papadimitriou et al., 2016) highlights a critical limitation. The effectiveness of LAB is influenced by factors such as soil type, climate, and microbial competition, indicating that localized solutions are essential for practical applications.

The role of LAB in plant protection and growth promotion further reinforces their potential as eco-friendly alternatives to agrochemicals. Studies documenting LAB's ability to produce phytohormones and suppress pathogens such as Botrytis cinerea and Erwinia carotovora (Trias et al., 2008; Daranas et al., 2019) provide strong evidence of their multifunctionality. More recent work by Ait Barka et al. (2023) and Choudhary et al. (2021) has demonstrated that LAB can activate systemic resistance and enhance abiotic stress tolerance in crops, strengthening their role as biostimulants. However, the strain-specific nature of these effects raises concerns about scalability. Unlike synthetic pesticides, which provide broad-spectrum protection, LAB require tailored strain selection for specific crops and regions. This adds complexity to their adoption and suggests a need for advanced screening methods and multi-strain consortia approaches (Martín et al., 2021; Kapse et al., 2023). In livestock systems, findings demonstrate LAB's potential to improve feed efficiency, gut health, and disease resistance (Dowarah et al., 2017; Mamuad et al., 2021). The use of LAB in silage inoculation also supports more sustainable animal production by improving fermentation quality and reducing methane emissions (Seo et al., 2022; Uyeno et al., 2015). Importantly, the reduction of antibiotic-resistant bacteria through LAB supplementation (Holman & Chénier, 2015; Rahman et al., 2023) highlights their public-health relevance, addressing one of the most pressing challenges in modern livestock production. However, similar to crop applications, outcomes in livestock are not universally consistent and depend on diet composition, dosage, and strain specificity (Kumar et al., 2022).

In the food sector, LAB emerge as valuable biopreservatives that align with consumer demand for natural and chemical-free products (Agriopoulou & Varzakas, 2022; Zheng et al., 2020). Their ability to produce bacteriocins, lactic acid, and other metabolites enhances food safety while improving nutritional profiles (Bintsis, 2021; Das et al., 2021). Still, their variable efficacy across food types indicates that matrix-specific strategies are essential for successful industrial application (Martín et al., 2021; Choudhary et al., 2021).

Taken together, these findings emphasize that LAB offer a holistic approach to sustainable farming by simultaneously enhancing productivity, reducing chemical reliance, and promoting environmental and human health (FAO, 2021; Nanjundappa et al., 2022). However, significant barriers remain. Regulatory inconsistencies, strain-specific performance, and limited large-scale trials restrict their wider adoption (Kapse et al., 2023; Kumar et al., 2022). Addressing these challenges requires interdisciplinary collaboration among microbiologists, agronomists, and policymakers to design context-appropriate strategies and establish enabling frameworks for commercialization.

6. Conclusion

The curent study highlights the multifunctional role of lactic acid bacteria (LAB) in promoting sustainable agriculture across soil, plant, livestock, and food systems. LAB enhance soil fertility, suppress plant pathogens, promote growth, improve livestock productivity, and ensure food safety through natural preservation methods. Their ability to replace or reduce reliance on chemical fertilizers, pesticides, and antibiotics positions them as valuable tools in addressing pressing agricultural and environmental challenges. Furthermore, their contribution to public health, particularly through reducing antibiotic resistance and extending food shelf life, reinforces their broader societal impact.

Despite these benefits, the findings reveal practical challenges such as strain specificity, environmental variability, and inconsistent regulatory frameworks. Overcoming these barriers will require context-specific trials, strain optimization, and interdisciplinary collaboration. Ultimately, the integration of LAB into farming practices represents a promising pathway toward eco-friendly, resilient, and health-promoting agricultural systems.

Author contribution

S.Z.A. conceptualized the study and supervised the overall review process. S.N.M. and S.S. conducted the literature search and data extraction. S.A.T. and S.M.A. analyzed and synthesized the findings. Z.C. and M.Y.S. contributed to data interpretation and figure preparation. S.A.K. and A.A.R. drafted the manuscript and assisted in formatting and reference validation. All authors critically reviewed, revised, and approved the final version of the manuscript.

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Competing financial interests

The authors have no conflict of interest.

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