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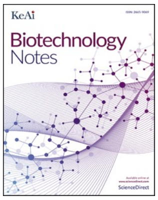

The role of Micro-biome engineering in enhancing Food safety and quality

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ABSTRACT

Microbiome engineering has emerged as a transformative approach to enhancing food safety and quality by strategically modulating microbial communities. This review critically examines state-of-the-art techniques, including synthetic biology, artificial intelligence (AI), and systems biology, that are revolutionizing our ability to improve nutritional profiles, extend shelf life, and optimize food production processes. The review further explores complex social, ethical, and regulatory considerations, emphasizing the importance of robust public engagement and the establishment of standardized frameworks to ensure safe and effective implementation. While microbiome engineering holds significant promise for revolutionizing food safety and quality control, further research is needed to address critical challenges, including understanding microbial dynamics in complex food systems and developing harmonized regulatory frameworks. By bridging interdisciplinary gaps, this paper underscores the necessity of collaborative efforts to unlock the full potential of microbiome-driven innovations for a more resilient and sustainable food industry.

1. Introduction

Food safety remains a critical global challenge,[1] exacerbated by the increasing complexity of global food supply chains, alongside the rising incidence of food-borne illnesses, spoilage, and contamination.[2] Food-borne diseases continue to represent a major public health concern, with millions affected annually, while antibiotic-resistant pathogens further complicate treatment efforts.[3,4] Moreover, food spoilage leads to substantial economic losses, as quality deterioration and nutrient degradation occur during processing and storage.[5] The pervasive use of synthetic chemicals, such as pesticides and preservatives, introduces additional health and environmental risks.[6,7]

In this context, microbiome engineering offers a novel and potentially transformative solution to these enduring food safety and quality challenges. By targeting the microbial communities that play integral roles in food production and preservation, microbiome engineering enables precise, controlled alterations to microbial populations. This approach draws on advancements in biotechnology, bioinformatics, and microbial ecology, aiming to enhance the functionality of microbiomes in a way that improves food safety, quality, and sustainability.[20] Microbiome engineering applications range from developing tailored probiotic and prebiotic products to enhancing crop resilience via plant-associated microbiomes.[21] By optimizing these microbial communities, it is possible to not only improve nutritional value but also extend shelf life, reduce spoilage, and minimize the reliance on synthetic preservatives and chemical additives, aligning with the growing consumer demand for natural and sustainable food production.[19,22] Fig. 1illustrates the key genome-editing tools-CRISPR-Cas9, TALENs, and ZFNs-that are fundamental to microbiome engineering. These tools enable targeted genetic modifications, facilitating improvements such as

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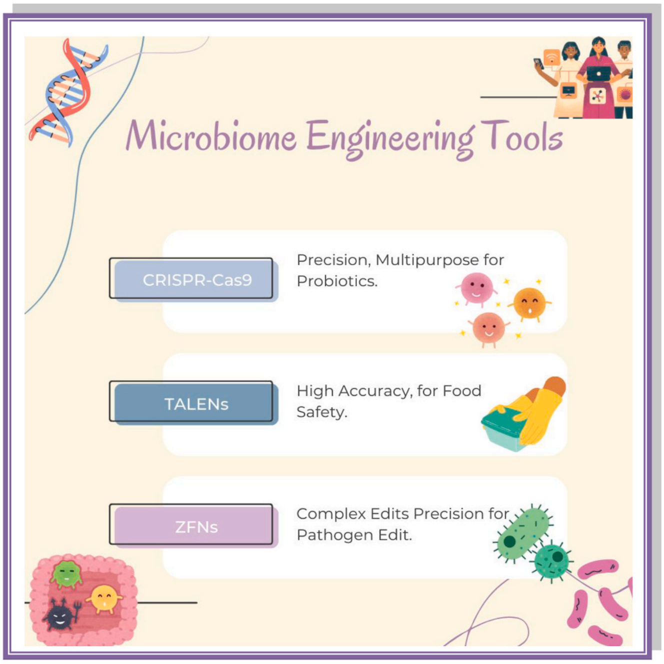


Fig. 1. Key tools in microbiome engineering.

enhancing probiotic functionality, controlling pathogens to improve food safety, and optimizing microbiomes for sustainable food production.

Additionally, the role of microbiomes in fermentation is critical. Fig. 2 illustartes the mechanism of fermentation in food production, emphasizing the metabolic pathways through which microbial activity contributes to flavor, texture, and preservation. The promise of microbiome engineering presents an innovative, holistic solution to the persistent challenges of food safety and quality. For instance, engineered probiotics can be used to modify gut microbiota, outcompeting harmful pathogens and reducing the risk of food-borne infections.[23–26] Furthermore, optimizing the microbiomes associated with fresh produce could reduce spoilage, thus eliminating the need for artificial preservatives.[27–29] Additionally, enhancing plant microbiomes can bolster crop resilience, contributing to food security and reducing chemical inputs.[30,31]

While the potential of microbiome engineering is substantial, realizing its full benefits requires addressing the scientific, technical, ethical, social, and regulatory challenges that accompany this emerging field. Ensuring public trust and developing standardized frameworks for the safe application of microbiome-based solutions are crucial for the sustainable progress of this area. This review evaluates the current state of microbiome research in food systems, assesses the limitations of traditional food safety approaches, and explores the opportunities for microbiome engineering to revolutionize food safety and quality.[32,33–35]

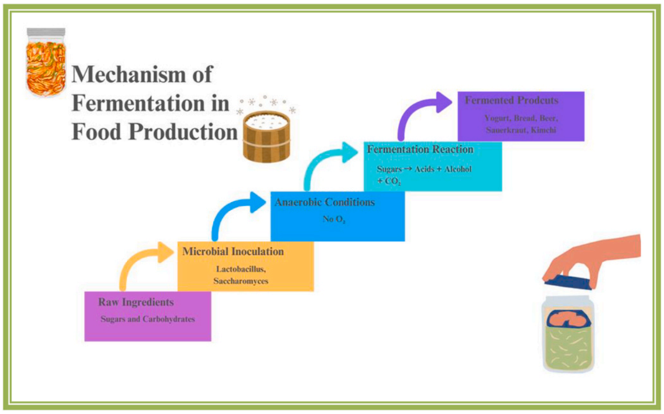


Fig. 2. Mechanism of fermentation in Food production.

2. The microbiome in food systems

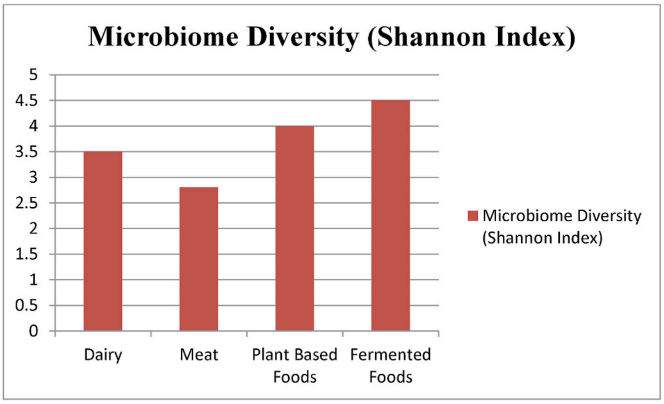
2.1. Diversity and role in different food matrices

The quality, safety, and type of food items are significantly influenced by their endogenous microbiomes-unique microbial communities that reside within various food types. Whether plant, dairy, or meat-based, each category hosts its own specific microbial populations, shaped by factors such as climate variability and anthropogenic environmental changes.[36,37] For instance, *lactic acid bacteria* (LAB), commonly found in dairy products, serve as crucial fermentation agents. By producing lactic acid, LAB lowers the pH of their surroundings, creating an inhospitable environment for pathogens and spoilage organisms. This acidification not only contributes to the preservation of dairy products but also enhances their flavor and texture through biochemical modifications of proteins and lipids during fermentation.[38] Furthermore, LAB in dairy products exhibit probiotic properties, promoting gut health upon consumption.[39]

When it comes to meat, the microbiomes are fermenters/spoilers by-and-large. Some bacteria, including those of the genera *Lactobacillus* or *Pediococcus*, can ferment meats such as salami to produce lactic acid and other antimicrobial agents which help prevent spoilage during storage.[40] Although, Into account need to be taken viruses and spoilage organisms such as *Salmonella* spp. *Listeria monocytogenes* are also part of the raw meat microbiome and responsible for food safety hazard.[41]

Microbiomes of plant-based diets are extremely diverse and can also be fluctuate widely based on locations, preparation methods etc. For example, the fermentation microbiomes are integral to processes such as those responsible for conferring unique textures and flavors into fermented sack cultured vegetables (*Lactobacillus* dominated; e.g., kimchi, sauerkraut.[42] In addition to that, the microbiome of fruits and vegetables contributes greatly to food decay (spoilage) as well as quality enhancement under fermentation.[43]

Lactic acid bacteria (LAB) are the main bacteria found in dairy products, playing a vital role in fermentation, flavor enhancement, and preservation.[8] In the context of meat Microbiomes, *Pseudomonas* and



Graph 1. | **Microbiome Diversity Index in different Foods.** It illustrates the Microbiomes present in dairy, meat, plant-based foods, and fermented foods using the Shannon Diversity Index. Fermented foods show the highest diversity score, indicating a rich variety of species, while meat and plant-based foods have slightly lower diversity ratings. Dairy ranks second in terms of diversity. The fermentation process likely contributes to the complex microbial ecosystems found in fermented foods, as it fosters a wide range of microbial life. The bars in the graph represent both the richness and evenness of microbial species across these different food groups.

LAB work together to inhibit pathogens and prevent spoilage.[9] In plant-based foods, LAB, yeasts, and molds contribute to fermentation and improve texture.[44] Fermented foods contain LAB, yeasts, and *acetobacter*, which are essential for food preservation and enriching its flavor profile.[11]

Overall, the diversity and dimensionality of Microbiomes in different food matrices demonstrate their importance for generating a plethora of flavors cooped with fermentative processes along with preservation. Overview of natural microbiomes and their functions in different food matrices can be seen in Table 1. Understanding and harnessing these Microbiomes could improve food quality, safety as well as aid in the development of new foods that may meet consumer demand for natural and minimally processed meals.[40]

2.2. *Contribution to fermentation, flavor development, and preservation*

Fermentation involves the biochemical transformation of sugars and other organic compounds into alcohol, carbon dioxide (CO_2), lactic acid, or their derivatives. These conversions are facilitated by diverse microorganisms, including yeasts, bacteria (e.g., lactic acid bacteria, LAB), and fungi (e.g., molds). This process plays a critical role in the production of a wide range of foods, such as dairy products, meats, vegetables, and beverages. The flavors, textures, and shelf stability of fermented foods are significantly influenced by how the microbiome modulates each stage of the process.

In dairy fermentation, LAB species such as *Lactococcus lactis*, *Streptococcus thermophilus*, and *Lactobacillus bulgaricus* ferment lactose into lactic acid, leading to the coagulation of milk proteins. This process not only produces cheese and yogurt but also enhances preservation by creating an acidic environment that inhibits the growth of spoilage microorganisms. Furthermore, secondary fermentations, such as the production of carbon dioxide and propionic acid in Swiss cheese, contribute to its characteristic texture and aroma.[38,39]

In meat fermentation, coagulase-negative staphylococci (CNS) play a crucial role in flavor development and preservation.[45] These microorganisms convert nitrates to nitrites, which facilitate the characteristic color formation in cured meats while also acting as a preservative. LAB species are instrumental in carbohydrate fermentation, producing lactic acid and other compounds that enhance texture, flavor, and shelf life. For instance, the interplay of LAB strains in sauerkraut fermentation reduces pH levels, yielding a stable and nutritious product with improved sensory properties.[46,42]

Fermentation of plant-based foods showcases the complex microbial interactions that convert carbohydrates into organic acids, alcohols, and gases. These natural processes improve digestibility, enhance nutrient bioavailability, and serve as a preservation method. By reducing dependency on artificial preservatives, these microbiome-driven processes align with the growing consumer demand for clean-label, minimally processed foods.[40]

Table 1
Overview of natural microbiomes and their functions in different food matrices.

Food Matrix	Dominant-Microbiomes	Functions	References
Dairy	Lactic acid bacteria (LAB)	Fermentation, flavor development, preservation	8
Meat	Pseudomonas, LAB	Spoilage prevention, pathogen inhibition	9
Plant-based Foods	Yeasts, molds, LAB	Fermentation, texture enhancement	10
Fermented Foods	LAB, yeasts, acetobacter	Flavor complexity, preservation	11

3. Microbiomes in food spoilage and pathogenesis

3.1. *Key spoilage organisms and pathogens*

While microbiomes are crucial for beneficial processes of food production like fermentation and preservation, they also play an important role in the spoilage of food as well as to cause or prevent foodborne illness. Spoilage organisms and pathogens are major problems in the food sector, since they can cause a large economic loss or substantial health hazards for consumers. Table 2 shows key spoilage organisms and pathogens in food systems provides an overview of the most significant microorganisms that contribute to food spoilage and foodborne illnesses.

These spoilage organisms cause the food quality to degrade by causing off odors, flavors and texture change. Pseudomonas species have been identified as major spoilage bacteria, which important cause of the degradation of meat and dairy products since it is repute for its ability to produce lipolytic and proteolytic enzymes hydrolyze proteins (fats-proteins).[43] Yeasts and molds of the genera *Saccharomyces*, *Aspergillus* can spoil plant material constituted foods. In addition, these organisms can ferment carbohydrates and generate off-odors as well as spoilage compounds.[39]

Conversely, pathogens are bacteria which lead to food-poisoning and bring severe health issues in relation to public. The most famous food-borne pathogens are bacteria like *Salmonella*, *Escherichia coli O157* and *Listeria monocytogenes* leading to severe illness or Death. These pathogens can contaminate food at any stage of its manufacturing, processing or distribution. It is usually caused by current or former infections from surfaces, water and other food stuffs.[38] *Listeria monocytogenes* is one of the most significant pathogens in ready-to-eat foods such as cheese, and milk, being more risky meat products because it can grow at a refrigerated temperature.[40] Examples of common pathogens that could increase during poor handling practices or due to cross contamination in processing are *Salmonella* and *E. coli*.[38] Together, these pathogens and spoiler bacteria in the food system emphasize the necessity of high-quality food safety practices as well as genetic modifications to potentially mitigate such risks.[47]

3.2. *Mechanisms of spoilage and food-borne illnesses*

Pathogens and spoilage organisms exploit diverse and intricate metabolic pathways to degrade food compounds, significantly impacting food safety and quality. These mechanisms often involve the production of specific metabolites, such as hydrogen sulfide, lactic acid, and acetic acid, as well as toxins like enterotoxins and Shiga toxins, which contribute to spoilage and food-borne illness. For instance, *Pseudomonas* species produce proteases and lipases that hydrolyze proteins and fats, resulting in undesirable sensory changes such as off-odors, sliminess, and rancidity in dairy and meat products. This enzymatic activity not only shortens the shelf life of perishable foods but also causes substantial economic losses.[39,43]

In plant-based foods, spoilage yeasts such as *Saccharomyces* and molds like *Aspergillus* ferment sugars into organic acids and ethanol, leading to off-flavors, textural degradation, and reduced consumer

Table 2
Key spoilage organisms and pathogens in food systems.

Spoilage Organism/ Pathogen	Food Products Affected	Mechanism of Action	References
Listeria monocytogenes	Dairy, meat	Invasion of host cells, toxin production	12
Escherichia coli O157	Fresh produce, ground beef	Shiga toxin production, adhesion	13
Salmonella spp.	Poultry, eggs	Cell invasion, immune evasion	14
Pseudomonas spp.	Meat, fish	Proteolysis, lipolysis	9

acceptability. Additionally, the production of secondary metabolites, including aflatoxins by molds, poses significant safety concerns. Fig. 3 illustartes the mechanisms underlying food spoilage and food-borne illnesses, highlighting the roles of specific pathogens and their metabolic by-products. A recent study by Liu et al. (54) highlighted the differential growth dynamics of spoilage organisms such as *Pseudomonas fluorescens* and *Brochothrix thermosphacta*, alongside pathogens like *Escherichia coli O157*:H7, *Salmonella* spp., and *Listeria monocytogenes* in both ground beef and plant-based meat analogues (soy- and pea-based).

In dairy systems, spoilage organisms such as *Lactococcus lactis* subsp. *lactis* can produce biogenic amines like histamine, which negatively affect product safety and sensory attributes, while lipase activity from *Pseudomonas fluorescens* exacerbates lipid oxidation and intensifies off-flavors.[48] Pathogens like Salmonella invade intestinal mucosa and release enterotoxins, disrupting cellular processes and causing symptoms such as fever, diarrhea, and abdominal cramping. Shiga toxin-producing strains of *E. coli*, such as O157:H7, secrete toxins that damage intestinal walls and, in severe cases, lead to renal failure. Meanwhile, *Listeria monocytogenes*, capable of growing at refrigeration temperatures, produces virulence factors that breach intestinal barriers, leading to systemic infections such as meningitis and septicemia, particularly in vulnerable populations.[38,40,41]

Understanding these mechanisms is critical for devising targeted control strategies. Advances in microbiome engineering and other innovative approaches offer promising solutions to mitigate spoilage and food-borne pathogens by modulating microbial communities responsible for these hazards, ensuring enhanced safety and prolonged shelf life for diverse food products.[49]

3.3. Case studies of notable outbreaks and spoilage incidents

Food borne outbreaks and spoiling episodes, for which there exist many published case studies involving spoilage organisms in combination with foodborne pathogens, serve as substantial evidence on the impact of both kinds of microbes to this end. These incidents demonstrate the perils of unsafe or mismanaged food systems and just highlight how important effective regulation remains.

One example is the 1993 *Escherichia coli* O157 outbreak in the United States associated with undercooked hamburger patties at a fast-food outlet. This outbreak resulted in over 700 cases of illness and four deaths, leading to substantial changes in food safety legislation such as the implementation of Hazard Analysis Critical Control Points (HACCP) for meat processing.[38]

In a similar vein, in 2008 deli meats contaminated with *Listeria monocytogenes* led to an extensive outbreak of the pathogen across Canada. An outbreak that led to 23 deaths and 57 confirmed cases of listeriosis underscored the severity with which this virus can affect processed and ready-to-eat foods.[40] It reminded everyone that you need strict controls in your processing facility–for example, to maintain a sanitary process and prevent cross-contamination.

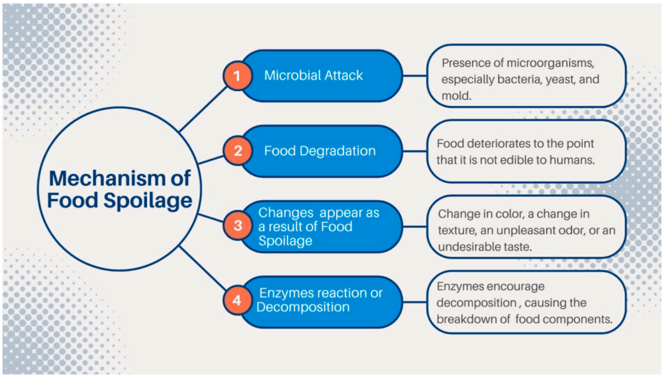


Fig. 3. Mechanism of Food spoilage and Food-borne Illness.

Donataus Kushner, a prominent Chinese melamine milk crisis case in 2008 is the best example of how adulteration and contamination have influentially led to spoiling food systems. This case serves to illustrate the need for monitoring all stages of food production, in order to preempt outbreaks even if not microbiologically driven.[40] As the case studies suggest, both for food industry public health reasons microbial contamination and spoiling can be disastrous. They also emphasize the importance of continuous development research and innovation in microbiome control as a means to enhance food safety and quality.[38]

4. Cutting-edge techniques in microbiome engineering

Microbiome engineering emerges as a potential platform for improving food quality and safety with the power to manage microbial ecosystems wisely. The advancement of technologies such as the visualization of metagenomics studies, support tools in synthetic biology and genetic engineering, bio-me-too probiotic products gene-editing technologies have reshaped our capacities to manage microbiomes that are at play both for producing food. Current breakthroughs of microbiome engineering, developments relevant to food systems, particularly those summarized in Table 3.

4.1. CRISPR-Cas9, TALENs, and other gene-editing tools

Genetic engineering is a powerful tool in microbiome engineering, enabling the precise elimination or enhancement of specific microbial traits. Among the many advances in this domain, gene-editing technologies such as CRISPR-Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats) and TALENs (Transcription Activator-Like Effector Nucleases) stand out for their transformative potential.

CRISPR-Cas9 has revolutionized genetic engineering due to its unmatched precision, efficiency, and versatility. It allows scientists to introduce mutations, deletions, or insertions at specific DNA loci within microbial genomes. In the food industry, CRISPR-Cas9 has been used to engineer beneficial microbes to perform more efficiently under fermentation conditions or to deactivate virulence genes in pathogenic bacteria, thereby enhancing microbiological safety and quality.[50] For instance, *Lactobacillus* strains used as probiotics have been successfully engineered using CRISPR-Cas9 to improve resilience in the intestinal environment and enhance gut colonization.[50]

In comparison, TALENs also enable targeted genetic modifications by binding specific DNA sequences and inducing double-strand breaks, which are then repaired by the cell's intrinsic mechanisms. While TALENs are known for their high accuracy and lower off-target effects, they are less frequently employed due to their complexity and labor-intensive design compared to CRISPR-Cas9. Nonetheless, TALENs are favored in applications requiring exceptionally precise genetic edits, where even minor off-target activity must be avoided.[8] This complementary relationship underscores the need for tailored approaches in genetic engineering based on specific use cases.

Beyond modifying individual microbial strains, gene-editing technologies have paved the way for engineering entire microbial consortia. By selectively altering the genomes of key microbial members, it is possible to optimize metabolic outputs, improve stability against

Table 3
Summary of genetic engineering tools in microbiome engineering.

Tool/ Technique	Applications	Example Studies	References
CRISPR-Cas9	Targeted gene editing	Engineering LAB for vitamin production	[15]
TALENs	Gene knockout	Modification of spoilage organisms	[16]
Synthetic Biology	Design of microbial consortia	Custom probiotics for gut health	[17]

environmental fluctuations, and promote synergistic interactions within the community.[51] This approach has significant implications for food safety and quality, particularly in developing robust starter cultures for fermentation processes.

Applications of engineered microbial consortia extend beyond food production. Synthetic microbial consortia (SMC) have emerged as promising tools for addressing global resource demands. Recent advances highlight their potential in waste degradation, hazardous substance mitigation, and converting biomass into high-value products. For instance, SMCs have been utilized in lignocellulosic biorefinery, where an engineered *Escherichia coli* consortium employing a glucose–xylose–phenolics (GXP) system achieved efficient conversion of lignin-derived phenolics into L-tyrosine, with yields reaching 86.4 %.[52] Additionally, co-cultures of *Monascus purpureus* and immobilized *Lactobacillus fermentum* have enhanced *Monascus* pigment production by 59.18 %, with omics analyses elucidating the underlying regulatory pathways.[53] These examples underscore the potential of microbial consortia to optimize bioproducts yields and promote sustainability. Further research into the construction and regulation of synthetic microbial consortia is essential to fully realize their potential in waste valorization, bioproducts synthesis, and environmental sustainability.[54]

4.2. Engineering microbial consortia for desired traits

Fermentation fosters the development of microbial consortia, which are communities of microorganisms interacting and evolving through various stages of food production. These consortia function as dynamic systems influenced by genetic and metabolic principles. Refactoring microbial consortia to exhibit desired traits is referred to as "engineering" microbial compositions and functions, aimed at achieving specific outcomes such as enhanced flavor profiles, extended shelf life, or improved nutritional quality.[55]

Synthetic biology plays a pivotal role in this process by enabling modifications to existing metabolic pathways or introducing new ones to optimize the functionality of microbial consortia. For instance, *lactic acid bacteria* can be reengineered to produce additional bioactive compounds, such as vitamins or peptides, thereby improving the nutritional properties of fermented foods.[56,57] Similarly, these consortia can be designed to generate natural preservatives like bacteriocins, which inhibit the growth of spoilage and pathogenic organisms, thereby extending the shelf life of food products.[50]

Advanced approaches in microbial engineering include manipulating quorum-sensing pathways to regulate gene expression in response to environmental signals. By engineering these pathways, microorganisms within a consortium can be programmed to synchronize their metabolic activities, enhancing control over fermentation processes and ensuring consistency in food quality. For example, quorum-sensing engineering has been used to manage bacterial communication, effectively "tricking" bacteria to respond in ways that optimize fermentation outcomes.[8,58,59]

The efficacy of engineered microbial consortia in food systems has been demonstrated through various case studies. For example, the combination of yeast and lactic acid bacteria in sourdough bread production has led to improved sensory attributes, extended shelf life, and resistance to spoilage organisms. Similarly, in dairy products, engineered consortia have enhanced the efficiency of lactose fermentation and aroma production, resulting in better-textured and more flavorful products.[56,50]

4.3. Success stories and current research

Genetic engineering and synthetic biology have been used to engineer the microbiome for improved food safety, quality with some notable successes. This has been reached through the construction of lactobacillus strains with enhanced probiotic and stress tolerances. CRISPR-Cas9 was also used to modify these strains, improving their resilience against acidic conditions such as the one of an individual's stomach and thus increasing both probiotic efficacy and survival rate.[50] This is important for the development of functional food supporting gut functionality as well.

Similar examples include the manufacturing of fermented plant-based foods with improved nutritional and sensory properties by engineering microbial consortia. Alterations of the metabolic pathways for some microbial strains within consortium caused to enhance major amino acids and bioactive agents, as a result that justifying development of superior flavor with more nutritional values.[8]

Even now, research is being carried out on microbiome engineering to enable the development of new food products that offer superior functional properties along with safety and quality using both synthetic biology as well gene-editing approaches. For instance, current work is focusing on the development of engineered probiotics that enable to direct bioactive compounds towards gut modulation which would provide new alternatives for developing functional foods with health benefits.[56] The replacement of foodborne pathogens by natural microorganisms is another interesting approach that shows huge potential to decrease the risk of food-related infections.[50]

5. Metagenomics and metabolomics

5.1. Advanced techniques for microbiome analysis

Advanced analytical techniques, such as metagenomics and metabolomics, have revolutionized the study of microbiomes in food systems, providing unprecedented insights into their structure and functionality. Recent advances in metagenomics and metabolomics for microbiome analysis are given Table 4. Metagenomics, a culture-independent approach, analyzes microbial communities directly from their environments by leveraging genomic material. This technique has not only uncovered previously uncultivable microorganisms but has also illuminated the intricate ecological interactions within microbial consortia, advancing our understanding of microbial diversity in food matrices.[12]

Metabolomics, in parallel, focuses on the comprehensive profiling of metabolites-the small molecules produced during microbial metabolism. By offering a biochemical snapshot of microbial activity, metabolomics elucidates metabolic interactions within microbiomes, revealing the pathways that drive critical processes such as fermentation, spoilage, and the biosynthesis of bioactive compounds. Together, these methodologies provide a multidimensional understanding of microbiota, integrating genetic potential with functional metabolic output.[60]

In the context of food systems, metagenomics plays a pivotal role in characterizing microbial communities across ingredients and production environments. This knowledge is essential for identifying spoilage organisms or low-abundance pathogens that may pose significant risks to food safety and quality. Complementarily, metabolomics enables a detailed examination of the biochemical mechanisms underlying microbial dynamics, offering critical insights into microbial transformations and their implications for food innovation.[61]

By synergistically employing metagenomics and metabolomics, researchers can decode the complexity of microbiota under dynamic conditions, paving the way for targeted interventions and optimization of food production processes. These transformative tools hold immense

Table 4
Recent advances in metagenomics and metabolomics for microbiome analysis.

Technique	Application	Key Findings	References
Metagenomic Sequencing	Community structure analysis	Discovery of novel microbes in dairy	[18]
Metabolomics	Metabolite profiling	Identifying spoilage biomarkers in meat	[19]
IntegratedOmics Approaches	Comprehensive microbiome analysis	Linking microbiome to food quality	[2]

potential to enhance food safety, quality, and sustainability, addressing the growing demands of a globalized food system.[60,62]

5.2. Applications in identifying and manipulating microbial communities

Recent advancements in metagenomics and metabolomics have revolutionized our ability to study, understand, and manipulate microbial communities to achieve targeted improvements in food quality and safety. Metagenomic analyses now enable real-time monitoring of microbial communities in food systems, such as hospital foods, allowing for the early detection of undesirable microorganisms that may lead to contamination or spoilage.[63] Such insights empower food producers to adopt proactive measures, including environmental modifications or the enrichment of specific beneficial microbial strains, to ensure a favorable microbiota composition.[64]

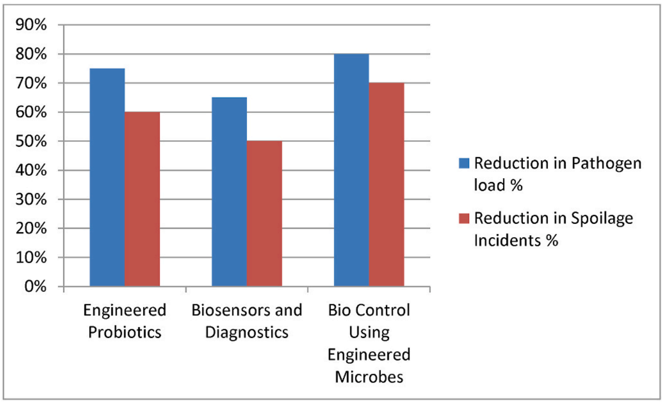
Metabolomics complements these efforts by identifying key metabolites that influence microbial activity. For instance, the chemical profiling of food-associated microbiomes has revealed biomarkers for spoilage and contamination, enabling precise interventions to mitigate these risks.[60] A notable example is the identification of spoilage-associated natural acids in meat products, which has informed strategies to inhibit the responsible bacteria and extend product shelf life.[63]

Furthermore, the integration of metagenomic and metabolomic data has facilitated the engineering of synthetic microbial consortia tailored for specific outcomes. These consortia might enhance flavor, texture, and bioactive compound production, potentially contributing to high-quality food products with improved taste and nutritional profiles. Additionally, microbiome engineering has been instrumental in designing safer food systems by enabling microbial degradation of toxic compounds or preventing the proliferation of pathogens.[65,61]

These cutting-edge approaches underscore the transformative potential of metagenomics and metabolomics in fostering innovative, safe, and sustainable food systems, paving the way for next-generation solutions in food science and technology.

5.3. Insights from recent studies

The synergy existing between metagenomics and metabolomics platforms highlights their efficacy in depicting the untold story of food-associated microbiomes as recently demonstrated by a number of studies. Metagenomic analysis has been used to probe the microbial interactions underpinning fermentation and flavor in these products by tracking bacterial diversity, assembly and functional gene content of traditional fermented foods–for example.[65] This information can be harnessed to optimize fermentation processes and develop new products with similar sensory qualities as traditional foods but higher consistency, safety and sustainability.



Graph 2. | Modern application techniques to manipulate the microbial community. The column-based graph 2 illustrates the effectiveness of various strategies in reducing pathogen load and spoilage events. Engineered microbes for bio-control lead the way, achieving a remarkable 70 % reduction in spoilage and an 80 % decrease in pathogen load. Following closely are engineered probiotics, which demonstrate a 75 % decrease in pathogen load and a 60 % reduction in spoilage. Lastly, biosensors and diagnostics, while showing the least impact, still contribute significantly with a 50 % decrease in spoilage events and a 65 % reduction in pathogen load. The graph clearly depicts the relative effectiveness of each intervention for ensuring food safety and preservation.

In a separate study, untargeted metabolomic profiling was performed to identify the key primary metabolites associated with spoilage of dairy products. The information on the pathways by which bacterial metabolisms cause spoilage led researchers to design ways of blocking these processes or making dairy products with longer shelf lives and higher quality.[60] This research shows the capability of metagenomics and metabolomics to enhance food quality and security, therefore causing creativity in innovation for novel food products.

6. Probiotics, prebiotics, and synbiotics

6.1. Engineering probiotics for specific functionalities

Probiotic design involves modifying microbial strains to enhance their functional capabilities, such as producing bioactive compounds directly at the site of action, colonizing the gut more effectively, or surviving for extended periods under harsh gastrointestinal conditions. These advancements have shifted attention toward probiotics-live beneficial bacteria that not only improve host health but also play a pivotal role in microbiome engineering, particularly in the development of functional foods. By employing genetic engineering, researchers have successfully enhanced probiotic strains, such as engineering *Lactobacillus* species to produce antimicrobial peptides (AMPs) that inhibit pathogenic bacteria in both food matrices and the gut environment. Additionally, probiotics can be genetically modified to synthesize vitamins, enzymes, or other bioactive molecules, enriching the nutritional and dietary value of food products.[66,56]

An emerging and innovative approach involves leveraging synthetic biology to create "designer probiotics" with entirely new functionalities. These probiotics are programmed with genes that enable them to sense and respond dynamically to specific environmental cues, such as producing therapeutic compounds or signaling the presence of pathogens. Such advances enable the development of functional foods with targeted health claims, including the prevention or treatment of gastrointestinal disorders, mitigation of food-borne infections, or maintenance of gut homeostasis.[66] These engineered probiotics represent a significant leap forward in food safety, quality, and personalized nutrition, offering promising avenues for addressing global health challenges.

6.2. Role of prebiotics in shaping beneficial microbiomes

Prebiotics are food ingredients, always soluble fiber carbohydrates that selectively nourish and stimulate the growth of some bacteria in your intestines. Prebiotics (encourage the growth of probiotics and other beneficial microorganisms) are important in shaping the gut microbiome community composition and activity, which is involved directly or indirectly to food safety/quality.[67,68]

What happens when these beneficial bacteria are present but the necessary food for them (like prebiotics) is not plentiful. One way to counter this is by enriching foods with prebiotics, which stimulate the growth of probiotics as well other beneficial bacteria in your digestive system. For example, prior studies have shown that addition of dietary fibers to food products-inulin or oligosaccharides-could stimulate the growth of *Bifidobacterium* and *Lactobacillus* species selectively inside human gastrointestinal tract which is very effective for improving gut health leading to decrease risk factors associated with gastrointestinal infections.[56]

Recent advances in the design of prebiotic formulations have centered on identifying new prebiotics that can be used to selectively target specific bacterial groups or metabolic pathways within the gut microbiome. Role of probiotics and prebiotics in microbiome engineering is given in Table 5. One example is the development of prebiotic compounds to selectively feed populations that produce butyrate (an anti-inflammatory short-chain fatty acid), which may hamper initiation and propagation of colorectal neoplasia.[67] The role of prebiotic research is being put in proper perspectives and recent developments are laying way for creation of functional meal to enhance food safety, quality along with its gut health aspects.

6.3. *Innovations in synbiotic formulations*

Not just this, there is a preventive and personalized range of drugs called synbiotics that offers profound balance to microbial engineering by combining the benefit of both probiotic as well prebiotic not something which exists in any other standalone products alone. Synbiotics function on the theory that the prebiotic component provides substrate for growth and metabolic action of a probiotic, rendering said probiotics more efficient in colonizing and affecting change in gut microbiota.[66]

Most of the advances in synbiotic formulation have been aimed at improving compatibility between probiotic and prebiotics components as well as functionality. As an example, synbiotic compositions combining specific Lactobacillus strains with tailored prebiotics have been developed to enhance the viability and engraftment of these bacteria in the colon.[56] Studies have shown that these synbiotics are beneficial for immune function, gut health and reducing GI illness. Innovation can even extend to the development of targeted synbiotics–a prebiotic specifically designed to promote growth of an established health beneficial probiotic strain. It provides personalized nutrition to improve the health of the gut and overall well-being by creating synbiotic products that are customized for specific medical conditions or dietary needs.[66]

Therefore, it can be concluded with certainty that advances secured in the perception of probiotics, prebiotics and synbiotics are gifting higher returns on food quality with respect to safety. Targeted prebiotics, synergistic synbiotic formulations and functionally engineered probiotics have made microbiome-based interventions more effective ways to improve gut health in addition for the prevention of food borne infections therefore help with better production of safe quality foods items. These developments underscore the importance of microbiome engineering toward the evolution of food science and nutrition.

7. Improving food quality and extending shelf life

Much promise has been demonstrated in use of microbiome engineering as an approach to improving food quality and extending shelf life. A further part explores novel microbiome interventions designed to prevent food deterioration and reduce allying with all round strategies for improving the nutritional and functional aspects of food. These food manufacturers can improve the quality and shelf life of their products by using bio-fortification, sensory optimization, and intentional microbiome management. It can reduce our impact on the environment and help pay for itself.[69,70]

Table 5
Role of probiotics and prebiotics in microbiome engineering.

Component	Role in Microbiome Engineering	Applications in Food Systems	References
Probiotics	Introducing beneficial bacteria to improve gut health and immunity	Fortified dairy products, fermented foods	35
Prebiotics	Non-digestible fibers that promote the growth of beneficial microbes	Added to cereals, snacks, infant formula	93
Synbiotics	Combination of probiotics and prebiotics for enhanced efficacy	Functional beverages, dietary supplements	94
Engineered Probiotics	Genetically modified bacteria for targeted functions	Enhanced yogurt strains, bioactive peptides production	95
Innovations in Prebiotics	Designing specific prebiotics for selective microbial stimulation	Customized food ingredients, targeted gut interventions	96

7.1. *Bio-fortification and nutrient enhancement*

In the field of microbiome engineering for biofortification, targeted microbial adjustments have demonstrated significant potential to enhance the nutritional value of foods. Unlike radical alterations to the human microbiome-a practice that may introduce unintended consequences-precision modifications to specific microorganisms, including viruses, bacteria, and fungi, can yield mutually beneficial outcomes. For example, strains such as *Bifidobacterium* and *Lactobacillus* have been engineered to overproduce essential micronutrients like folate and B-vitamins in fermented dairy products. Notably, *Limosilactobacillus fermentum* increased protein digestibility from 62.60 % to 90.75 % following 16-h fermentation, while iron and zinc bioavailability improved by 39 % and 14 %, respectively.[71] similarly, engineered staple crops with optimized microbiomes demonstrate improved micronutrient uptake and conversion efficiency, addressing deficiencies in communities reliant on these crops. For instance, *Weissella cibaria* BAL3C-5 C120T was shown to enrich oat-based beverages with riboflavin (3.4 mg/L), dextran (3.2 g/L), and prebiotic oligosaccharides such as panose (6.6 g/L) after 24 h of fermentation under optimized conditions.[72]

Additionally, bio-fortified probiotics such as engineered strains capable of producing vitamin B12 offer a sustainable and affordable alternative to synthetic supplements, particularly beneficial for individuals adhering to vegetarian and vegan diets. These innovations align with global public health initiatives by addressing micronutrient deficiencies and providing enriched, functional foods that support diverse populations. By integrating biofortified products into the food system, we can contribute to combating malnutrition while enhancing dietary quality and accessibility on a global scale.[73,9,74]

7.2. *Engineering for improved sensory qualities (taste, texture)*

Food's sensory properties, including flavors, textures, and aromas, play a pivotal role in shaping consumer preferences, determining whether a particular food is perceived favorably. The engineering of these sensory attributes is increasingly facilitated through microbiome editing, especially in fermentation processes, where the flavor profiles are heavily influenced by the microbial composition. The selection and design of specific microbial strains are crucial for minimizing the production of undesirable off-flavors while maximizing the synthesis of desirable flavor compounds during food processing.[75–77] One illustrative example can be seen in the fermentation of dairy products such as cheese and yogurt, where complex microbial interactions not only contribute to the fermentation process but also significantly impact the final flavor and texture profiles. For instance, microbiome engineering can elevate the concentrations of alcohols, esters, and aldehydes, thus enhancing the complexity and richness of the flavor. Moreover, texture modification in fermented foods can be achieved through the engineering of microorganisms to produce exopolysaccharides, which increase viscosity and improve mouth-feel, as seen in products like yogurt and kefir.[78,79]

With the continuous advancements in microbiome engineering, it is becoming increasingly feasible to create innovative food products with superior sensory qualities. For example, sourdough bread made using engineered lactic acid bacteria cultures exhibits improved texture, contributing to a better crumb structure, enhanced flavor, and longer shelf life, compared to bread made with traditional starters.[80] These advancements highlight the potential of microbiome engineering to optimize and sustain the sensory attributes of food products, aligning with consumer expectations and preferences for more flavorful and appealing foods.

7.3. Evidence from recent advancements

Recent studies have found that microbiome engineering overcomes this limitation, by modulating the nutritional profile and organoleptic characteristics of food products. Examples include designing probiotic strains that maximize the bioaccessibility of iron in plant-based diets. When administered alone, these probiotics have a higher efficacy in increasing iron bioavailability if provided during high-iron meals[81] resulting in low rates of anemia.[8] This use of engineered yeast in winemaking produces wines with more reliable flavor profiles and lower concentrations of unwanted byproducts such as ethyl carbonate and acetaldehyde.[82,44]

We can say that microbiome engineering is now real, and producing food products with great sensorial attributes and also a sound nutritional background. Who knows, once the technology advances even further we might get to see more innovative applications that take consumer satisfaction and ultimately food quality up a notch.

8. Microbiome interventions for shelf life extension

To strengthen this example, let's consider its implications in the food industry-extending the shelf life of different types of food products is critical as it helps reduce waste (particularly in higher spoilage goods), increases food security and enhances supply chain efficiency. Microbiome engineering provides novel strategies to prevent spoiling and extend freshness with enormous societal implications for the environment as well as the economy.[83–85]

8.1. Strategies to inhibit spoilage organisms

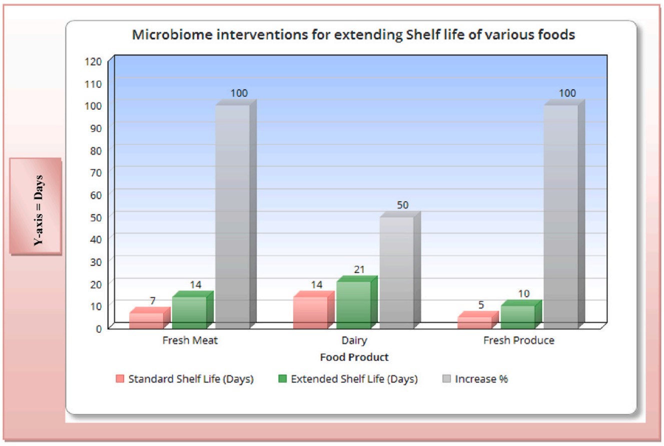
In dairy products, on the other hand, spoilage organisms–yeasts and molds as well as bacteria are responsible for food deterioration and loss of quality. Traditional spoilage control strategies, such as packing, refrigeration and channeling chemicals do not seem to possess the best influence on food quality.[7] In contrast, microbiome engineering could out compete spoilage species for their resources by redesigning microbial communities to decrease them naturally since its affects on the ecosystem are focused and enduring.

One approach is the introduction of competitive exclusion principles, whereby beneficial microorganisms are selected or engineered to outcompete spoilage species for both resources and niche. For instance, modified *Lactobacillus* strains have been engineered to produce antimicrobial peptides which inhibit the growth of bacteria that cause spoilage in prepared meats such a species as *Listeria* and *Clostridium*.[44] Similarly, improved microbial stability can be realized by incorporating engineered lactic acid bacteria to ferment dairy products that express bacteriocins and organic acids which inhibit spoilage organism growth.[10]

A further approach could be the use of bio-protective cultures-i.e. *lactobacilli* adapted to enhance resistance and safety of food matrices. Since these cultures can be adapted to different food matrices, they serve as an attractive means of prolonging shelf life that offers versatility. However, it has been shown that the inoculation of bioprotective cultures can significantly prolong shelf life fermented vegetables due to their ability inhibit molds and spoilage yeasts proliferation.[11]

8.2. Case studies of prolonged freshness and reduced waste

A substantial variety of examples show how effective microbiome engineering can be in protecting food from going bad and reducing waste. Modified Lactobacillus cultures have been used to extend the shelf life of meat products by up to 50 % and reduced spoilage rates.[86] It also reduces financial losses from spoiling by giving consumers higher quality items.



Graph 3. | Microbiome interventions for extending Shelf life of various foods. It illustrates the extended shelf life of various food items due to longer preservation methods. Fresh meat and produce see their shelf life double, increasing from 7 to 14 days for meat and from 5 to 10 days for produce, which represents a 100 % increase. In contrast, dairy products experience a 50 % increase, extending their shelf life to 21 days. Overall, the graph effectively highlights the advantages of shelf-life extension across different food categories, with fresh produce and meat showing the most significant improvements.

In the dairy industry, microbiome engineering has prolonged milk and cheese shelf life extensively. Microfiltered milk treated with engineered probiotics, for example, has been shown to exhibit an extended shelf life compared to conventionally processed (pasteurized homogenized) milk and a reduction in spoilage organisms as well as maintaining quality over storage period.[87] Similarly, engineered lactic acid bacteria were found to inhibit spoilage molds in cheese manufacture by a couple of weeks and additionally increase the shelf life.[88]

So here it is, actual cases where microbiome engineering in food can be put to the test. By enhancing the stability and safety of food products, microbiome-based interventions have an impact on everything from reducing food waste to impacting manufacturing costs, optimizing overall supply chain efficiencies.

8.3. Economic and environmental benefits

The integration of microbiome engineering to extend food shelf life offers both profound environmental and economic advantages. From an economic perspective, prolonged shelf life directly reduces food spoilage, which in turn minimizes production and retail costs associated with waste.[89,90] This reduction in spoilage enhances profitability for producers and retailers. Additionally, extended shelf life results in fewer consumer trips to the grocery store, thereby decreasing food waste and reducing overall grocery bills.

The environmental impact of reducing food waste is significant: food waste decomposing in landfills produces methane, a potent greenhouse gas. By strategically modifying the microbiome, microorganisms can be harnessed to mitigate spoilage during packaging and storage, thus curbing waste generation. This approach also offers the potential to decrease reliance on chemical preservatives, which are often toxic to both human health and the environment.[91,92]

For food producers, microbiome-based solutions present a sustainable alternative to traditional methods, enabling the development of safer, cleaner products that meet consumer demand for simplified ingredients and clean labels. As microbiome engineering technologies evolve, they hold promise not only for improving food quality and extending shelf life but also for enhancing the nutritional value of crops.

These innovations contribute to a more sustainable and efficient food system, providing substantial benefits to both the economy and the environment, while supporting the broader goal of sustainability.

9. Regulatory, ethical, and social considerations

9.1. Regulatory frameworks and guidelines

The regulatory landscape for microbiome engineering is multifaceted, with significant variability across regions. Regulatory bodies are pivotal in ensuring that microbiome-based interventions for food safety adhere to robust standards of safety, efficacy, and quality. In the United States, the Food and Drug Administration (FDA) employs the Generally Recognized as Safe (GRAS) framework for assessing the safety of microorganisms in food. However, this framework does not fully encompass genetically modified microbiomes; particularly those developed using advanced synthetic biology techniques like CRISPR or multiplexed gene editing. The regulatory gap highlights the need for tailored guidelines addressing the complexities of engineered microbiomes. Oversight for environmental safety is further provided by the Environmental Protection Agency (EPA), which evaluates the release of genetically modified microorganisms into the environment. Regulatory Frameworks for Microbiome Engineering in Food Systems," provides a detailed comparison of these regulatory frameworks across key regions given in Table 6. In the European Union, the European Food Safety Authority (EFSA) assesses microbiome-based interventions under the Novel Food Regulation (EU) 2015/2283 and guidelines for genetically modified organisms (GMOs). Additional oversight from the Directorate-General for Environment ensures compliance with environmental safety standards. Japan and Canada have also established distinct frameworks, such as the Food Sanitation Law and Novel Foods Regulation, respectively, to regulate microbiome-related products.[73,9]

9.2. Challenges in regulatory approval processes

There are a number of regulatory challenges along the path to being approved for microbiome engineering. Main problems as there are no established rules targeted especially to microbiome products this will cause developers to face possible approval process and regulation differences that might occur between different areas.[75]

Another challenge is the need for rigorous data demonstrating that modified microbiomes are safe and effective; This often requires lengthy and expensive studies to assess potential hazards and benefits, including clinical trials as well as animal testing. The complex nature of microbiomes that include the interactions between multiple species, as well as bacteria and host, add another layer to risk assessment challenge.[78]

Regulatory agencies will also have to grapple with the unknown future risks of setting loose GMOs into the environment. This includes assessing the ecological consequences of microbial strains that may spread outside their desired applications and affect other species or ecosystems.[79]

9.3. Consumer perceptions and acceptance of engineered microbiomes

Consumer perception and acceptability are the key components for having such microbiome engineering in successful practice at large scale of food production. It has been shown that public enthusiasm toward microbiome-based innovations is high, but consumer attitudes can vary a great deal based on perceived risk and benefit associated with the technology.[78,97]

These surveys, show that, provided microbiome engineering comes with proven health benefits and transparent information, consumers are generally on board. For example, individuals appear more willing to consume engineered probiotics for specific health applications such as improved digestion or increased nutrient uptake.[81] There are myriad ethical considerations that come with microbiome engineering. There is a concern about unintended consequences associated with these genetic changes. Ethical frameworks should consider the long-term effects on biodiversity, air pollution and human health as well. For example, there is concern that designer bacteria might persist in the environment and interact to unknown effect with local populations of microbes.[44,98,99]

Second, the potential for differential access and equity in care raises additional ethical concerns. As microbiome engineering technologies are further developed, there is a risk of unequal distribution of benefits–with some people or countries benefiting less than others. In the application and commercialization of microbiome engineering, more should be done beyond just availability to maintain access balances and discrepancy.[10]

10. Emerging technologies and innovations

10.1. Potential breakthroughs on the horizon

Several emerging technologies can establish this context and contribute to the field of microbiome engineering as regards food safety & quality. One of the intriguing subjects to explore here is about developing advanced metagenomic and metabolomic assays that can provide thorough information on microbiome compositionist, as well its tasks. Therefore, these resources can enrich our understanding of the connections between microbiota and aid in developing targeted therapies.[100,101,102]

Another is the application of synthetic biology to come up with microbes that perform well for specific targeted functions. Refinements of gene editing tools like CRISPR/Cas9 may enable precise engineering of the genomes microorganisms, for example to create lineages that exhibit more robust probiotic effects or have rendered higher levels resistance against food spoiling organisms.[103] This edited line of microorganisms could offer new possibilities for improved food quality and extended

Table 6
Regulatory frameworks for microbiome engineering in food systems.

Region	Regulatory Body	Key Guidelines/Regulations	Examples of approved products	References
United States	Food and Drug Administration (FDA)	Generally Recognized as Safe (GRAS) status, Novel Foods regulations	• Nisin-producing Lactococcus lactis as a biopreservatives. • Genetically modified yeast for enhanced ethanol production.	73
	Environmental Protection Agency (EPA)	Environmental safety evaluations for genetically modified microorganisms.	• Engineered Bacillus subtilis strains for biofilm prevention in food processing environments.	73,75
European Union	European Food Safety Authority (EFSA)	Novel Food Regulation (EC) No 258/97	• Lactobacillus plantarum WCFS1 as a probiotic strain. - Natamycin-producing fungi for dairy preservation.	9
	Directorate-General for Environment	Environmental safety requirements for the release of genetically modified microorganisms.	–	
Japan	Ministry of Health, Labor, Welfare	Food Sanitation Law	• Traditional probiotic strains such as *Lactobacillus casei Shirota* for gut health.	73

Legend.
FDA: Food and Drug Administration; EFSA: European Food Safety Authority; GRAS: Generally Recognized as Safe.

shelf life.

Another source of innovation is the fusion of microbiome research with machine learning and artificial intelligence. AI algorithms could accelerate the development of new microbiome-based products and interventions by allowing complex high-dimensional data from the host as well as its associated microorganisms in *meta*-omics experiments to be tested for associations, trends be discovered, or microbial behavior forecasted.[104,105]

10.2. Integration with other food technologies

The microbiome engineering then couples with other food technology, and creates some quite explosive opportunities. One example is that blockchain technology could be used when combined with microbial engineering for traceability to make food safety and transparency better. The blockchain technology ensures an unchangeable, safe record of microbiome-based treatments from the production point to consumer's table and therefore allows having full transparency on where food is coming from.[106,107]

Moreover, the combination of microbiome engineering with food packaging technology may yield intelligent packaging systems. Immobilizing biosensors across these systems for the monitoring of microbial activity, where additional data are needed on making food products to assess their quality and safety could be incorporated.[107]

10.3. Multidisciplinary approaches to microbiome engineering

An interdisciplinary approach combining biology, genetics, bioinformatics and food engineering is likely to shape the future direction of microbiome engineering. Cross-disciplinary collaboration can breed new and more comprehensive solutions, and innovative applications. For example, the future of food processing would integrate microbiome research with cutting-edge technology to take advantage of beneficial microbes for enhancing its sensorial and health-promoting features by optimizing probiotics (edible microorganisms) and prebiotics in some foods.[48,108]

When it comes to complex questions such as the long-term effects of microbial therapies on human health and planet we live, in multifaceted research can shine. By coming together in new ways across disciplines, we can engineer more durable and sustainable solutions for breweries seeking to process microbiome engineering.

11. Identifying and addressing research gaps

11.1. Key areas lacking sufficient research

While tremendous advancements have been achieved, a number of crucial microbiome engineering topics still require additional scrutiny. Gaining deeper insight into the long-term consequences of customized microbiomes on human health and our surroundings is absolutely imperative. Extensive research across time is essential to thoroughly assess potential dangers and uncertain outcomes, even though short-term studies may yield helpful data.[109,110]

Furthermore, creating standardized practices for judging the protection and efficiency of innovations influenced by microbiomes is another field lacking sufficient exploration. The intricacy of microbial interplay may not be completely understood through current evaluation techniques, which can yield inconsistent results. Ensuring uniformity and reliability of findings necessitates establishing clear processes and measures.[110,111] We also need further inquiry on the socioeconomic impacts of microbiome engineering. This involves appraising the cost-effectiveness of microbiome-based solutions and comprehending their possible effects on consumer behaviors, market dynamics, and food security.[112,113]

11.2. Collaborative efforts between academia, industry, and government

Academia, business and government agencies should now take collective ownership of the knowledge gaps that is preventing microbiome engineering technology from progressing. Although industry can assist in putting research results into practical use and commercial products, academia still has a say in the development of basic research pass innovative ideas. Governmental bodies play a big role in setting standards, funding studies and research & fostering cooperation.[114,115]

Establishing collaborative research projects and public-private partnerships can help to close the divide between what we know from science about implementation. These collaborations enable the best from both worlds to be combined accelerating innovation and development of commercial microbiome-based products.[116] International collaboration will also be important in sharing ideas and skills which can help to develop this area internationally.[117] In conclusion, microbiome engineering holds the promise of food quality and safety enhancement in future. By focusing on new approaches and techniques, addressing missing pieces of knowledge, driving interdisciplinary research initiatives that foster collaboration we can inspire creativity and make significant strides in our understanding this fascinating domain.

12. Conclusion

This review highlights the revolutionary effects that food safety and quality improvements can have through microbiome engineering. Combining advanced technologies like synthetic biology, as well as artificial intelligence with new food technology or formats allow food preservation, nutritional and sensory aspects can be improved greatly. To resolve difficult problems of long standing, the research stresses the importance of filling in gaps with long-term studies, standardizing techniques and socio-economic impact analysis. To overcome current obstacles and move forward in the future, cooperation between government, business and academia is essential. Microbiome engineering promises to give us fresh and innovative ways of making a living, which will affect the future food quality for better altogether as it further grows.

CRediT authorship contribution statement

Anand Kumar: Writing – original draft. **Abhishek Bisht:** Writing – review & editing, Conceptualization, Visualization. **SammraMaqsood:** Writing – review & editing. **SaiqaAmjad:** Writing – review & editing. **Sapna baghel:** Writing – review & editing. **Swapnil Ganesh Jaiswal:** Writing – review & editing. **Shuai Wei:** Supervision.

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