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Microbial Safety Challenges and Control Strategies in Legume-based Foods- A Global and Indian Perspective: A Review

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ABSTRACT

Legumes are an important component of the Indian diet and serve as a major source of protein, dietary fiber, minerals and bioactive compounds, particularly among vegetarian populations. India is the world's largest producer and consumer of pulses and the growing demand for plant-based foods, sprouts, ready-to-eat products and dairy alternatives has significantly expanded the legume processing sector. However, increasing commercialization and consumption of these products have also raised concerns regarding microbial contamination and foodborne illnesses caused by pathogens such as *Salmonella spp.*, *Escherichia coli*, *Listeria monocytogenes* and *Bacillus cereus*. This review critically examined recent national and international literature on microbial contamination, foodborne outbreaks, pathogen survival mechanisms and food safety management in legumes and legume-based foods, with special emphasis on Indian production systems, storage conditions and processing practices. Traditional and advanced microbial control approaches including thermal processing, fermentation, ultraviolet irradiation, cold plasma, ultrasound-assisted sanitation, microwave heating and plasma-activated water treatments were also evaluated. The review identified contaminated irrigation water, poor post-harvest handling, inadequate sanitation during storage and processing and limited cold-chain infrastructure as major factors contributing to microbial contamination in legumes and pulse-based foods. Previous studies reported that *Salmonella* accounted for nearly 37-50% of legume-associated outbreaks globally, while *Listeria monocytogenes* was frequently linked with recalls of ready-to-eat products. Advanced microbial intervention technologies demonstrated significant effectiveness, with several approaches achieving 3-7 log reductions in pathogenic microorganisms while preserving nutritional and sensory quality. Emerging products such as sprouts, fermented legume foods, plant-based dairy alternatives and ready-to-eat pulse products were found to be particularly vulnerable to microbial contamination.

Key words: Food processing, Food safety, Foodborne pathogens, Legumes, Microbial contamination, Plant-based foods, Pulses, *Salmonella*, Sustainable nutrition.

Legumes are among the earliest domesticated crops and have remained a vital part of human nutrition for centuries due to their rich nutritional composition, affordability and contribution to sustainable food systems. They play an important role in ensuring food and nutritional security, particularly in developing countries. Major leguminous crops include chickpea (*Cicer arietinum*), pigeon pea (*Cajanus cajan*), lentil (*Lens culinaris*), mung bean (*Vigna radiata*), urd bean (*Vigna mungo*), cowpea (*Vigna unguiculata*), soybean (*Glycine max*), field pea (*Pisum sativum*) and groundnut (*Arachis hypogaea*). These crops are extensively cultivated across tropical and subtropical regions and are consumed in diverse forms such as whole grains, split pulses, flour, sprouts, fermented foods, snacks and protein-enriched processed products (FAO, 2023; Jha *et al.,* 2022).

India holds a significant position in global pulse production and consumption, contributing nearly 25% of the world's total pulse output while also being the largest consumer of pulses worldwide. Pulses are cultivated annually on nearly 28-30 million hectares, with production exceeding 27 million tonnes in recent years (Dixit and Naik, 2025). Major pulse-producing states include Madhya Pradesh, Maharashtra, Rajasthan, Uttar Pradesh, Karnataka, Andhra Pradesh, Tamil Nadu and Punjab. In the Indian dietary system, pulses serve as a primary and economical source of protein, especially for the large vegetarian population.

Legumes are highly valued for their exceptional nutritional profile and their role in addressing malnutrition

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and protein deficiency. Depending on the crop species and variety, legumes generally contain 18-40% protein along with substantial amounts of dietary fiber and resistant starch. They are also rich in essential minerals such as iron, zinc, calcium, magnesium and potassium, as well as vitamins including folate and thiamine. Furthermore, legumes contain bioactive compounds such as flavonoids, phenolics, antioxidants and phytochemicals that are associated with several health-promoting properties, including reduced risks of cardiovascular diseases, diabetes and obesity (Zahir *et al.,* 2026). The nutritional composition of major legumes commonly consumed in India, presented in Table 1, was compiled from recent scientific studies and international pulse databases.

Beyond their nutritional significance, legumes contribute substantially to agricultural sustainability and environmental health. Through symbiotic association with *Rhizobium* bacteria, legumes possess the unique ability to fix atmospheric nitrogen biologically, thereby reducing the requirement for synthetic nitrogen fertilizers. This process improves soil fertility, enhances soil organic carbon and supports sustainable cropping systems. In India, legumes are increasingly recognized as climate-resilient crops because they require comparatively less water than major cereals such as rice and wheat, making them suitable for water-limited and rainfed regions (Singh *et al.,* 2023).

In recent years, the global demand for legume-based foods has increased considerably due to the growing popularity of vegetarianism, vegan diets, functional foods and plant-based nutrition. Products derived from legumes, including soy milk, tofu, tempeh, hummus, pulse-based pasta, protein isolates, meat alternatives, fermented foods and sprouts, are gaining widespread acceptance in urban and international markets. The rapid expansion of the plant-based food sector is largely driven by increasing consumer awareness regarding sustainability, health benefits and animal welfare concerns (Joshi and Kumar, 2022; FAO, 2023).

The present review was undertaken to provide a comprehensive overview of microbial safety concerns and control measures associated with legumes and legume-based food products. Relevant literature was collected from widely recognized scientific databases, including scopus, web of science, PubMed, science direct and google scholar. The review primarily considered studies published between 2000 and 2025, along with relevant reports and guidelines issued by national and international food safety organizations.

A systematic search was conducted using keywords and combinations of terms such as legumes, pulses, microbial contamination, foodborne pathogens, food safety, *Salmonella*, *Escherichia coli*, *Listeria monocytogenes*, *Bacillus cereus*, sprouts, plant-based foods and microbial control technologies. The search was refined through the use of Boolean operators to ensure the retrieval of relevant and high-quality publications.

The selection process focused on studies reporting microbial hazards, contamination sources, foodborne outbreaks, pathogen survival, storage and processing practices and intervention strategies related to legumes and their derived products. Special attention was given to publications addressing conditions relevant to India, including production systems, post-harvest handling and food processing environments. Peer-reviewed journal articles, review papers, technical reports and publications from reputable organizations were included in the analysis.

Expanding legume processing industry and food safety concerns

The rapid commercialization and industrial-scale processing of legumes have created both new market opportunities and important food safety concerns. Traditionally, legumes were mostly consumed after domestic cooking and conventional processing practices that effectively reduced microbial contamination. However, modern food systems increasingly rely on minimally processed, ready-to-eat, refrigerated, fermented and convenience-based legume products. These products typically pass through several stages of handling, transportation, storage, packaging and distribution, thereby increasing the possibility of microbial contamination during the supply chain (Behera *et al.,* 2024; WHO, 2024).

In India, the food processing industry has expanded rapidly due to urbanization, changing dietary habits, rising disposable incomes and the growing demand for convenient and value-added foods. The pulse processing sector involves numerous operations such as cleaning, grading, milling, polishing, soaking, sprouting, roasting, extrusion, fermentation, packaging and preparation of ready-to-cook and ready-to-eat products. While these

Table 1: Nutritional composition of major legumes commonly consumed in India.

Legume crop	Protein (%)	Carbohydrates (%)	Fiber (%)	Fat (%)	Major minerals
Chickpea	20-22	55-60	12-15	5-6	Iron, phosphorus
Lentil	24-26	58-60	10-12	1-2	Iron, zinc
Mung bean	22-24	55-58	8-10	1-2	Potassium, magnesium
Urd bean	23-25	56-58	11-13	1-2	Calcium, iron
Soybean	36-40	25-30	8-10	18-20	Calcium, phosphorus
Cowpea	22-24	56-60	10-12	1-2	Iron, potassium

Source: Adapted from Jha *et al.* (2022), FAO (2023).

technologies improve shelf life, product quality and consumer convenience, they may also create favorable conditions for contamination by pathogenic microorganisms if proper hygiene and safety measures are not maintained (FSSAI, 2023; Kumar and Singh, 2022).

Foodborne illnesses remain a major global public health issue, affecting millions of people every year through contaminated food and water. In recent years, legume-based foods have increasingly been associated with outbreaks caused by important bacterial pathogens such as *Salmonella* spp., *Escherichia coli*, *Listeria monocytogenes*, *Bacillus cereus* and *Clostridium perfringens*. These microorganisms can contaminate legumes at multiple stages, including cultivation, harvesting, storage, processing, packaging and retail handling. Table 2 summarizes the major foodborne pathogens associated with legumes and legume-derived foods, along with their sources and associated health risks, based on recent microbial food safety studies (Behera *et al.,* 2024; WHO, 2024).

Among these pathogens, *Salmonella* has emerged as one of the most critical contaminants in low-moisture legume products. Several international outbreaks linked to peanut butter, sprouts, tahini, hummus and soybean-based foods have demonstrated the ability of this pathogen to survive for prolonged periods under dry storage conditions. Studies have further indicated that low moisture levels and high fat content can enhance the thermal resistance of pathogens, thereby reducing the effectiveness of conventional heat treatments used during processing (Finn *et al.,* 2013).

The growing popularity of sprouted legumes has also raised significant food safety concerns. Sprouting conditions generally involve warm temperatures, high humidity and nutrient-rich environments, all of which favor rapid microbial growth. Even a small level of initial contamination present on seeds can multiply substantially during germination. Since sprouts are frequently consumed raw or only minimally cooked, they carry a comparatively higher risk of transmitting foodborne pathogens to consumers (WHO, 2024).

In India, street-vended legume-based foods such as chaat, sprouts, boiled chickpeas, fermented batters and traditional snacks are widely consumed. However, these foods are often prepared and sold under inadequate hygienic conditions. Poor sanitation, use of contaminated water, improper storage, lack of refrigeration and inadequate temperature management significantly contribute to microbial contamination and increase the risk of foodborne diseases among consumers (FSSAI, 2023; Sharma *et al.,* 2022).

Sources and routes of microbial contamination in legumes

Microbial contamination of legumes can occur at multiple stages throughout the entire farm-to-fork continuum, beginning from cultivation and extending to final consumption. These contamination sources are generally classified into pre-harvest, harvesting, post-harvest, processing, transportation, storage, retailing and household handling stages. Each stage presents unique opportunities for the introduction, survival and proliferation of pathogenic microorganisms, thereby affecting the microbial safety and quality of legume-based foods (FAO, 2023).

Pre-harvest contamination primarily originates from soil, irrigation water, organic manures, fertilizers, insects, birds, animals and environmental exposure. The application of untreated farmyard manure and the use of contaminated irrigation water are considered major routes for introducing pathogenic microorganisms into agricultural fields. In many developing countries, practices such as flood irrigation and wastewater irrigation further increase the risk of contamination by bacteria, fungi, viruses and parasites (WHO, 2024).

During harvesting and threshing operations, legumes may become contaminated through direct contact with soil, harvesting equipment, workers, storage surfaces and transportation materials. Delayed drying after harvest creates favorable environmental conditions for microbial growth and mycotoxin production, particularly under warm and humid conditions. Similarly, excess moisture accumulation during storage significantly promotes the proliferation of fungi and bacteria. The contamination pathways and associated microorganisms presented in Table 3 were compiled from recent literature focusing on microbial hazards during legume cultivation, storage and processing systems (Behera *et al.,* 2024).

In rural regions of India, traditional pulse storage systems commonly involve gunny bags, open storage spaces and mud-based structures. These storage methods often expose legumes to high humidity, insect

Table 2: Major foodborne pathogens associated with legumes and legume products.

Pathogen	Common legume products affected	Major symptoms
Salmonella spp.	Sprouts, peanut butter, chickpea products	Fever, diarrhea, vomiting
E. coli O157:H7	Raw sprouts, salads	Bloody diarrhea, kidney complications
Listeria monocytogenes	Ready-to-eat hummus, refrigerated foods	Septicemia, meningitis
Bacillus cereus	Cooked pulses, stored foods	Vomiting, diarrhea
Clostridium perfringens	Cooked beans, canned products	Abdominal cramps
Staphylococcus aureus	Street foods, processed snacks	Food poisoning

Source: Adapted from Behera *et al.* (2024); WHO, (2024).

infestation, rodent activity and fungal contamination. Inadequate storage infrastructure and poor post-harvest handling practices contribute substantially to both quantitative and qualitative losses in pulses during storage (Kumar *et al.,* 2022).

Cross-contamination during processing is another critical food safety concern in the legume industry. The use of shared equipment, insufficient cleaning and sanitation, contaminated processing water and poor personal hygiene among workers can facilitate the transfer of pathogens from raw materials to processed foods. Ready-to-eat legume products are particularly susceptible because they often undergo limited or no heat treatment prior to consumption, allowing pathogens to survive and pose health risks to consumers (FSSAI, 2023).

The use of contaminated water during soaking and sprouting operations further increases microbial loads in legumes. Several studies have shown that pathogenic microorganisms can strongly attach to seed surfaces and develop biofilms, which are highly resistant to conventional washing and sanitization procedures. In some cases, bacteria may even internalize into sprout tissues during germination, making decontamination extremely difficult and increasing the potential risk of foodborne outbreaks associated with raw sprouts (Finn *et al.,* 2013).

Microbial safety challenges in emerging plant-based foods

The rapid growth of plant-based foods and alternative protein products has significantly transformed global food systems in recent years. Increasing consumer awareness regarding health, sustainability and environmental concerns has accelerated the demand for plant-derived foods such as meat analogues, dairy alternatives, protein beverages, fermented products and functional foods prepared from legumes. Proteins derived from soybean, pea, chickpea, lentil and mung bean are now extensively utilized in the formulation of these products due to their high nutritional quality, functional properties and affordability (Paul *et al.,* 2026; FAO, 2023).

Despite being widely perceived as healthier and environmentally sustainable alternatives, plant-based foods are not exempt from microbial safety concerns. These products possess complex physicochemical characteristics that can significantly influence microbial growth and survival. Factors such as high protein content, elevated water activity, fat concentration and abundant nutrient availability may create favorable conditions for microbial proliferation when products are improperly processed, stored, or handled. The information summarized in Table 4 was compiled from recent scientific studies focusing on microbial hazards associated with emerging plant-based and pulse-derived food products (WHO, 2024; Boukid, 2021).

Plant-based dairy alternatives, including soy milk, almond milk blends, pea-protein beverages and fermented legume drinks, often contain high moisture levels and near-neutral pH conditions that favor the growth of spoilage microorganisms and pathogenic bacteria. Failure to maintain proper refrigeration during storage and distribution can rapidly accelerate microbial multiplication and product deterioration. Similarly, protein-rich plant-based meat analogues may support the survival and growth of pathogens if adequate thermal processing, hygienic handling and sanitation practices are not strictly followed during manufacturing (Paul *et al.,* 2026).

Fermented legume products generally exhibit improved microbial safety because beneficial microorganisms produce organic acids and antimicrobial metabolites that inhibit pathogenic microbes. Traditional and industrial fermentation processes can therefore enhance both shelf

Table 3: Major contamination sources in the legume supply chain.

Stage	Contamination sources	Potential microorganisms
Pre-harvest	Soil, irrigation water, manure	*Salmonella*, *E. coli*
Harvesting	Equipment, workers, dust	*Bacillus*, *Staphylococcus*
Storage	Moisture, insects, rodents	Fungi, bacterial pathogens
Processing	Machinery, cross contamination	*Listeria*, *Salmonella*
Retailing	Poor hygiene, temperature abuse	Multiple pathogens
Household handling	Improper cooking and storage	Food spoilage organisms

Source: Adapted from Sharma *et al.* (2022), FAO (2023) and Behera *et al.* (2024).

Table 4: Emerging legume-based foods and associated microbial risks.

Product type	Common raw materials	Major food safety concerns
Plant-based milk	Soybean, pea	*Listeria*, spoilage bacteria
Meat analogues	Soy protein, pea protein	Cross contamination
Sprouts	Mung bean, alfalfa	*Salmonella*, *E. coli*
Fermented foods	Soybean, lentil	Improper fermentation
Ready-to-eat snacks	Chickpea flour, pulses	Moisture contamination

Source: Adapted from Behera *et al.* (2024), Sethi and Tyagi (2022) and WHO (2024).

life and nutritional quality. However, uncontrolled fermentation under poor hygienic conditions may still permit the growth of undesirable microorganisms, including spoilage bacteria, molds and toxin-producing species, thereby compromising food safety and product quality (Tamang *et al.,* 2020; WHO, 2024).

The increasing export of Indian pulse products and processed legume foods has further emphasized the importance of complying with stringent international food safety standards. Export consignments contaminated with pathogenic microorganisms or failing microbial quality specifications may face rejection in global markets, resulting in considerable economic losses, reduced market competitiveness and damage to consumer confidence. Therefore, maintaining high standards of hygiene, processing, storage and microbial quality assurance has become essential for the sustainable growth of the pulse processing and plant-based food industries in India (APEDA, 2024; FSSAI, 2023).

Need for food safety strategies and future perspectives

Ensuring the microbial safety of legumes and legume-based foods requires a comprehensive and integrated approach involving farmers, food processors, researchers, policymakers, regulatory agencies and consumers. Conventional thermal processing methods such as boiling, roasting, pasteurization, canning and sterilization continue to play a crucial role in reducing microbial contamination and improving food safety. These methods are widely used because of their effectiveness in inactivating pathogenic microorganisms and extending shelf life. However, modern food industries increasingly demand innovative technologies that can enhance microbial safety while preserving the nutritional, functional and sensory qualities of food products (Misra *et al.,* 2023; WHO, 2024).

In recent years, several emerging non-thermal technologies have gained considerable attention as effective alternatives or supplements to conventional thermal processing. Technologies such as cold plasma, plasma-activated water, ultraviolet (UV) irradiation, pulsed light, microwave heating, ultrasound treatment, high-pressure processing and ozone treatment have demonstrated promising results in reducing microbial populations in legumes and pulse-derived foods. Many studies have reported microbial reductions ranging from 3-7 log cycles for important foodborne pathogens using these advanced interventions. Table 5 summarizes the major emerging technologies used for microbial decontamination in legumes, along with their mechanisms of action and industrial applications based on recent food engineering and food safety studies (Singh *et al.,* 2023; Misra *et al.,* 2023).

Among these technologies, cold plasma and plasma-activated water have attracted significant research interest due to their ability to inactivate microorganisms at low temperatures without causing major changes in food quality. Similarly, high-pressure processing and ultraviolet treatments have shown effectiveness in extending shelf life and improving microbial safety in minimally processed and ready-to-eat legume products. These advanced technologies are particularly important for preserving heat-sensitive nutrients, flavors and textures that may otherwise be affected by conventional thermal treatments (Bourdoux *et al.,* 2022; Misra *et al.,* 2023).

In addition to processing technologies, predictive microbial modeling and artificial intelligence (AI)-based food safety systems are emerging as valuable tools for monitoring and controlling contamination risks across food supply chains. These systems help predict microbial growth and survival under different storage, transportation and processing conditions, thereby assisting industries in improving hazard control, shelf-life prediction and risk assessment strategies (Kumar and Singh, 2022).

In India, improving microbial safety in legumes requires strengthening food safety regulations, enhancing post-harvest infrastructure, promoting hygienic processing and storage practices and increasing awareness among consumers and food handlers. Capacity-building programs and training initiatives for farmers, processors, street vendors and food workers can play a significant role in minimizing contamination risks throughout the supply chain. Effective implementation of food safety standards and good manufacturing practices is essential for ensuring the safety and quality of both domestic and exported pulse products (FSSAI, 2023; APEDA, 2024).

Future research should focus on developing affordable and scalable microbial intervention technologies suitable for Indian agricultural and processing conditions. Greater emphasis is also needed on understanding pathogen behavior in traditional legume-based foods,

Table 5: Advanced technologies for microbial control in legume foods.

Technology	Mechanism	Advantages
Cold plasma	Reactive oxygen species	Non-thermal microbial reduction
UV irradiation	DNA damage	Surface decontamination
Microwave heating	Rapid internal heating	Reduced processing time
Ultrasound	Cell disruption	Improved sanitation
High-pressure processing	Membrane damage	Nutrient retention
Ozone treatment	Oxidative stress	Chemical-free sanitation

Source: Adapted from Misra *et al.* (2023) and Singh *et al.* (2024).

improving rapid microbial detection systems and designing sustainable processing methods that maintain both food safety and nutritional quality. With the growing global demand for plant-based and protein-rich foods, microbial safety management in legumes will continue to be an important area of scientific research, technological innovation and industrial development in the years ahead (FAO, 2023; WHO, 2024).

Survival mechanisms of foodborne pathogens in legume foods

The survival and persistence of foodborne pathogens in legume-based foods are influenced by several intrinsic and extrinsic factors, including moisture content, water activity, temperature, pH, nutrient composition, fat content, storage environment and processing conditions. Unlike many conventional food products, several legume-derived foods possess physicochemical characteristics that allow pathogenic microorganisms to survive for extended periods without a substantial decline in viability. Understanding the mechanisms responsible for pathogen persistence in legume matrices is therefore essential for developing effective microbial control measures and ensuring food safety throughout the supply chain (Samtiya *et al.,* 2022).

One of the most critical factors affecting microbial survival in legumes is low moisture content. Several pulse-based products such as roasted chickpeas, peanut butter, pulse flours, protein powders and dried beans are categorized as low-moisture foods. Traditionally, such foods were considered microbiologically safe because reduced water activity restricts microbial growth. However, research conducted over the last two decades has clearly demonstrated that pathogens such as *Salmonella* spp. and *Escherichia coli* can survive for prolonged periods under dry conditions while retaining their infectivity (Finn *et al.,* 2013). In some cases, low water activity environments may even increase the thermal resistance of pathogens, making them more difficult to eliminate during conventional heat treatments.

The survival ability of *Salmonella* in low-moisture legume products has been widely documented. Foodborne outbreaks associated with peanut butter in the United States demonstrated that *Salmonella* could persist in high-fat and low-water activity foods for several months (Sithole *et al.,* 2022). Similar persistence has also been observed in products such as chickpea flour, tahini, roasted pulses and soybean meal. The high fat content present in several legume products can create a protective barrier that limits heat transfer and shields microbial cells from thermal injury during processing. The major factors affecting microbial persistence in legume foods, summarized in Table 6, were adapted from recent investigations related to pathogen survival under different storage and processing conditions (Misra *et al.,* 2023).

Temperature is another major determinant influencing microbial survival and proliferation in legume-based foods. Storage under warm and humid conditions promotes rapid microbial growth, especially in cooked, minimally processed and ready-to-eat products. In tropical countries such as India, storage at ambient temperatures without proper refrigeration significantly increases food safety risks. Many bacterial pathogens exhibit rapid growth within the temperature range of 25-40°C, particularly when moisture levels are high (WHO, 2024).

Sprouted legumes provide exceptionally favorable conditions for microbial multiplication because sprouting involves soaking seeds in water followed by germination under warm and humid conditions. These environmental conditions activate seed metabolism and release nutrients that support rapid microbial proliferation. Studies have shown that pathogen populations may increase by 4-6 log cycles during sprouting when contaminated seeds are used (Ding *et al.,* 2013). Fig 1 illustrates the survival and multiplication of foodborne pathogens during different stages of legume sprouting under warm and humid conditions based on recent studies related to microbial safety in sprouts and minimally processed foods (Behera *et al.,* 2024).

Another important mechanism contributing to pathogen persistence is biofilm formation. Biofilms are structured communities of microorganisms attached to surfaces and enclosed within extracellular polymeric substances. Pathogens such as *Listeria monocytogenes*, *Salmonella* spp. and *E. coli* can form biofilms on food processing equipment, storage containers, pipelines and other food-contact surfaces (Hua and Zhu, 2024). Biofilm formation enhances microbial resistance against sanitizers, thermal treatments and environmental stresses, thereby making microorganisms more difficult to eliminate during routine cleaning and sanitation procedures.

Table 6: Factors influencing survival of foodborne pathogens in legume foods.

Factor	Influence on microbial survival	Examples
Low water activity	Increases survival duration	Roasted pulses, peanut butter
High fat content	Enhances thermal resistance	Soy products, peanut products
Neutral pH	Supports microbial growth	Plant-based milk
Warm temperature	Accelerates multiplication	Sprouts
High humidity	Promotes spoilage and fungi	Improper storage
Biofilm formation	Protects pathogens	Processing equipment

Source: Adapted from Misra *et al.* (2023).

The chemical composition of legume foods also plays an important role in determining pathogen behavior and survival. High protein and fat contents in soy-based products may protect microorganisms during thermal processing, while carbohydrates and dietary fibers can influence water-binding capacity and microbial stability. Plant-based milk alternatives prepared from soybean, pea, almond and oat provide nutrient-rich environments that can readily support bacterial growth if refrigeration and hygienic handling are inadequate (Paul *et al.,* 2026).

Apart from bacterial contamination, fungal growth represents another significant challenge in stored legumes. Fungi such as *Aspergillus*, *Penicillium* and *Fusarium* can proliferate under improper storage conditions and produce harmful mycotoxins that pose serious health risks to consumers. Among these, aflatoxin contamination in groundnut and maize-based products is of particular concern in tropical and subtropical regions. The information summarized in Table 7 was compiled from recent studies emphasizing fungal contamination, aflatoxin occurrence and associated foodborne health hazards in improperly stored legumes (Sharma *et al.,* 2022).

Foodborne pathogens surviving in legume products may also develop stress adaptation responses that enhance their resistance to unfavorable environmental conditions. Exposure to desiccation, osmotic stress, acidic environments and sublethal heat treatments can induce cross-protection mechanisms, enabling microorganisms to survive subsequent processing interventions. These adaptive responses make microbial control strategies more challenging for food industries and processors (Finn *et al.,* 2013).

Recent investigations have further revealed that certain pathogens can enter a viable but non-culturable (VBNC) state under stressful environmental conditions. In this physiological state, microorganisms remain metabolically active but cannot be detected using conventional culture-based methods. Once favorable conditions are restored, these pathogens may regain activity and potentially cause foodborne illness, thereby posing an additional challenge for microbial detection and food safety management systems (Li *et al.,* 2023).

Foodborne outbreaks associated with legumes products

Foodborne outbreaks associated with legumes and legume-derived foods have increased significantly in recent decades due to the growing consumption of minimally processed, ready-to-eat and convenience-based products. Outbreaks linked to contaminated sprouts, peanut butter, hummus, tahini, soy products and pulse-based snacks have emphasized the critical importance of microbial safety management throughout legume food supply chains (WHO, 2024).

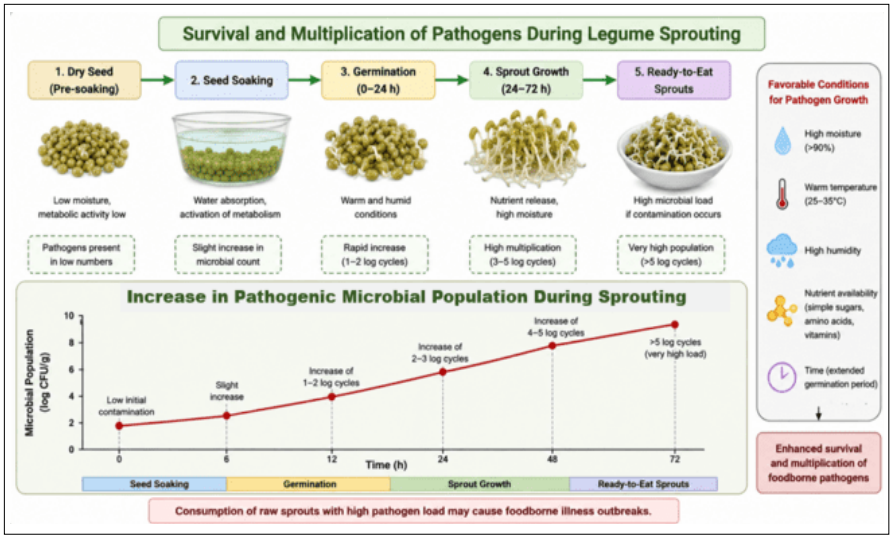


Fig 1: Survival and multiplication of pathogens during legume sprouting.

Table 7: Common fungal contaminants and associated mycotoxins in legumes.

Fungal species	Major mycotoxin	Health effects
Aspergillus flavus	Aflatoxin	Liver cancer, toxicity
Penicillium spp.	Ochratoxin	Kidney damage
Fusarium spp.	Fumonisins	Gastrointestinal disorders
Aspergillus parasiticus	Aflatoxin B1	Carcinogenic effects

Source: Adapted from FAO (2023), Sharma *et al.* (2022) and WHO (2024).

Among all legume-associated products, sprouted seeds have attracted the greatest attention because of their high susceptibility to microbial contamination. Numerous outbreaks involving *Salmonella* spp. and *Escherichia coli* O157:H7 have been associated with alfalfa sprouts, mung bean sprouts, fenugreek sprouts and mixed sprout products. One of the most serious foodborne outbreaks occurred in Germany in 2011, where contaminated fenugreek sprouts were linked to an outbreak caused by *E. coli* O104:H4, resulting in thousands of illnesses and several fatalities (Buchholz *et al.,* 2011). The outbreak highlighted the serious risks associated with contaminated seeds and the challenges involved in ensuring microbial safety in sprout production systems.

Peanut butter outbreaks have further demonstrated the remarkable ability of pathogens to survive in low-moisture foods. Several outbreaks reported in the United States involved contaminated peanut products that affected hundreds of consumers and led to extensive product recalls. These incidents challenged the long-standing assumption that low-moisture foods are inherently microbiologically safe. Studies revealed that pathogens such as *Salmonella* could survive for prolonged periods in peanut butter and similar products while retaining infectivity. Table 8 summarizes important global outbreaks associated with legume-based foods, including the responsible pathogens and their public health impacts based on recent foodborne disease reports and investigations.

The microbiological safety of legume-based foods remains a significant concern despite their nutritional benefits (Kamboj and Nanda, 2018). Processing and storage conditions can influence the survival of microorganisms and affect product quality and safety (Kamalasundari *et al.,* 2019). Recent studies on peanut products have highlighted the importance of appropriate processing interventions to maintain product quality and safety (Sakthi *et al.,* 2022). Furthermore, the growing consumption and commercial importance of peanut-based foods emphasize the need for effective quality control measures throughout the production chain to ensure consumer safety (Balasubramanian *et al.,* 2020).

In India, outbreaks specifically linked to legumes are relatively underreported due to limitations in surveillance systems and outbreak monitoring infrastructure. Nevertheless, microbial contamination in street foods, sprouts and pulse-based ready-to-eat products remains a major public health concern. Several studies conducted in Indian urban markets have reported high microbial loads in sprouted legumes and street-vended pulse products, mainly due to poor hygienic practices, inadequate sanitation and the use of contaminated water during preparation and handling (Sharma *et al.,* 2022; FSSAI, 2023). Fig 2 presents major foodborne outbreaks associated with legume-based foods worldwide, highlighting contaminated products, causative pathogens, affected countries and associated public health impacts based on recent international outbreak investigations and food safety reports (WHO, 2024).

The economic consequences of foodborne outbreaks are substantial and affect both public health systems and food industries. Product recalls, trade restrictions, healthcare expenditures, loss of consumer confidence and legal liabilities impose significant financial burdens on governments and food processing industries. Export-oriented sectors are especially vulnerable because importing countries enforce strict microbial safety standards and quality regulations (FAO, 2023).

The increasing globalization of food supply chains has further complicated outbreak management and traceability. Contaminated raw materials originating in one country can rapidly spread across international markets through complex distribution networks. As a result, the development of effective traceability systems, rapid microbial detection technologies and coordinated international food safety monitoring systems has become increasingly important for minimizing outbreak risks and improving food safety management in global food systems (WHO, 2024).

Advanced methods for microbial control in legume foods

Microbial control in legume-based foods involves the integration of traditional preservation methods and advanced food processing technologies aimed at minimizing microbial contamination while maintaining nutritional and sensory quality. Conventional preservation techniques such as boiling, roasting, drying, fermentation, canning, pasteurization and sterilization continue to play a vital role in ensuring the microbial safety and shelf stability of legumes and pulse-derived products (Behera *et al.,* 2024; WHO, 2024).

Among these methods, thermal processing remains one of the most effective strategies for controlling foodborne pathogens. Boiling legumes at temperatures above 100°C

Table 8: Major international outbreaks associated with legume foods.

Year	Product	Pathogen	Country	Impact
2011	Fenugreek sprouts	*E. coli O104:H4*	Germany	Thousands affected
2008	Peanut butter	*Salmonella typhimurium*	USA	Large product recall
2016	Hummus	*Listeria monocytogenes*	USA	Multiple recalls
2014	Bean sprouts	*Salmonella*	UK	Foodborne illnesses
2021	Soy products	*Listeria*	Canada	Product withdrawal

Source: Adapted from WHO (2024) and Behera *et al.* (2024).

effectively destroys most vegetative bacterial cells and significantly reduces microbial loads. Pressure cooking and commercial sterilization are extensively used in canned pulse products to achieve long-term microbial stability and safety. However, certain low-moisture legume foods may exhibit increased thermal resistance, requiring optimized heat treatments and carefully controlled processing conditions to ensure complete microbial inactivation (Misra *et al.,* 2023).

Fermentation represents another important and widely practiced preservation strategy in traditional legume foods. Fermented products such as tempeh, miso, natto, idli, dosa batter, soy sauce and dhokla contain beneficial microorganisms capable of producing organic acids, bacteriocins and various antimicrobial metabolites that inhibit the growth of pathogenic bacteria and spoilage microorganisms. In addition to improving microbial safety, fermentation also enhances flavor, digestibility and nutritional quality. The information presented in Table 9 was adapted from recent studies discussing traditional food processing techniques and their role in microbial control of legumes and plant-based food products (Paul *et al.,* 2026; Tamang *et al.,* 2020).

Modern food industries are increasingly adopting non-thermal technologies that effectively reduce microbial contamination while preserving the sensory and nutritional properties of food products. Among these technologies, cold plasma treatment has gained considerable attention due to its ability to generate reactive oxygen and nitrogen species that damage microbial cells without causing excessive heat generation (Misra *et al.,* 2023). This technology has shown promising results in the decontamination of seeds, sprouts, pulse flours and minimally processed foods.

Ultraviolet (UV) irradiation is another important non-thermal intervention that inactivates microorganisms by damaging microbial DNA and disrupting cellular replication. It is commonly applied for surface decontamination of seeds, sprouts, packaging materials and food-contact surfaces. Similarly, ultrasound treatment utilizes cavitation effects to disrupt microbial cell membranes and reduce microbial populations in liquid and semi-solid food systems. Fig 3 illustrates both traditional and advanced technologies used for microbial control in legumes, highlighting their mechanisms of action, industrial applications and contributions toward improving food safety and shelf life based on recent food preservation and food engineering studies (Misra *et al.,* 2023; Singh *et al.,* 2023).

Other advanced technologies such as high-pressure processing, pulsed electric fields, microwave heating and ozone treatment are also gaining increasing importance in the food industry. These technologies offer significant advantages by improving microbial safety while preserving flavor, texture, color and nutrient composition in legume-

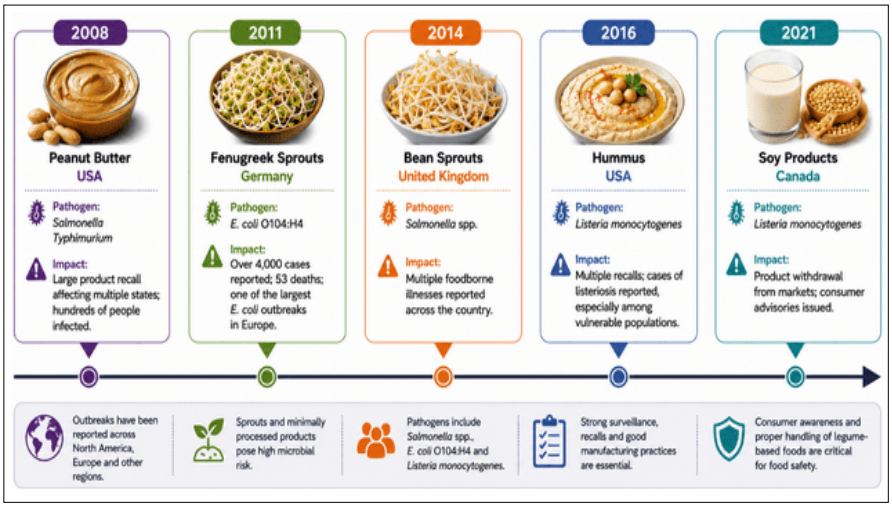


Fig 2: Major outbreaks associated with legume-based foods worldwide.

Table 9: Traditional microbial control methods used in legume foods.

Method	Mechanism	Common applications
Boiling	Heat destruction	Pulses, beans
Roasting	Moisture reduction	Snacks, flour
Fermentation	Acid production	Idli, dosa, tempeh
Drying	Water activity reduction	Pulse storage
Canning	Sterilization	Processed beans

Source: Adapted from Misra *et al.* (2023), FAO (2023) and Sethi and Tyagi (2022).

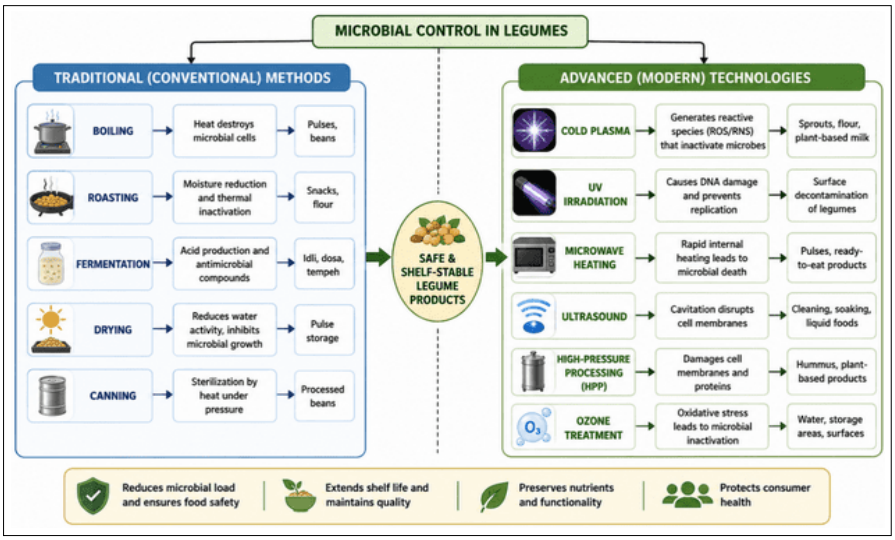


Fig 3: Traditional and advanced technologies for microbial control in legumes.

based products. Their application is especially valuable in minimally processed and ready-to-eat foods where maintaining product quality is essential (Bourdoux *et al.,* 2022).

Biological preservation strategies involving probiotics, bacteriophages, essential oils, plant extracts and natural antimicrobial compounds are emerging as sustainable alternatives to synthetic chemical preservatives. In addition, research on edible coatings and antimicrobial packaging materials is expanding rapidly due to increasing consumer preference for clean-label and environmentally friendly food products (Kumar and Singh 2022).

Future food safety systems are expected to increasingly adopt hurdle technology approaches, where multiple preservation methods are combined to maximize microbial reduction while minimizing undesirable effects on food quality. The integration of thermal, non-thermal, biological and intelligent monitoring systems may provide more efficient and sustainable solutions for ensuring the microbial safety of legumes and plant-based foods in the coming years (FAO, 2023; WHO, 2024).

FUTURE PERSPECTIVE

Future research should focus on understanding pathogen behavior in traditional Indian pulse-based foods, developing low-cost and sustainable decontamination technologies, improving rapid microbial detection systems, and exploring integrated hurdle technology approaches for enhanced food safety. Special attention should also be directed toward microbial risks associated with emerging plant-based foods and alternative protein systems. Overall, ensuring microbial safety in legumes and legume-based foods is essential for achieving sustainable nutrition, public health protection, food security, and the long-term growth of the plant-based food sector both in India and globally.

CONCLUSION

Legumes and legume-based foods play a crucial role in providing affordable nutrition, supporting food security, and promoting sustainable agriculture, especially in India. Despite their benefits, these foods can become contaminated with harmful microorganisms such as *Salmonella*, *E. coli*, *Listeria monocytogenes*, *Bacillus cereus*, and *Clostridium perfringens* during cultivation, processing, storage, or distribution. Products such as sprouts, ready-to-eat pulse foods, and plant-based alternatives are particularly vulnerable to microbial contamination. Challenges including poor hygiene practices, contaminated water sources, inadequate storage facilities, and limited cold-chain infrastructure further increase food safety risks.

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Disclaimers

The opinions and interpretations presented in this article are those of the authors alone and may not necessarily reflect the views of their affiliated institutions. Every effort has been made to ensure the accuracy and reliability of the information included in this review.

Informed consent

This manuscript is a review article developed using information from previously published scientific literature. As no experiments involving humans or animals were conducted by the authors.

Conflict of interest

The authors declare that there is no conflict of interest related to the publication of this review article. The study was conducted independently and no financial support or external agency influenced the collection of literature, interpretation of findings, manuscript preparation, or decision to publish.

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