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Application of Microbial Fermentation Technology in Improving Food Safety and Shelf Life

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Abstract: As a food processing technology with a long history, microbial fermentation has shown its unique advantages in safety control and quality extension in the modern food industry. The fermentation process produces antibacterial substances such as organic acids and bacteriocins through microbial metabolism, which can effectively inhibit the growth and reproduction of pathogenic bacteria and spoilage bacteria. At the same time, the reduction of pH value and the regulation of water activity caused by fermentation have created environmental conditions that are not conducive to the growth of microorganisms for food. In many fields, such as dairy products, meat products, fermented beverages and cereal and vegetable products, fermentation technology has achieved large-scale application, significantly improving the microbial safety and shelf life stability of products. By optimizing strain selection and controlling process parameters, fermentation technology is gradually replacing some chemical preservatives, providing a more natural and healthy preservation solution for the food industry, which has broad application prospects and research value.

Keywords: microbial fermentation; Food safety; Extended shelf life; Antibacterial substances; Organic acids

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1. Introduction

Food safety and shelf-life control have always been the core challenges facing the food industry. With the continuous growth of consumers' demand for natural and healthy food, the application of traditional chemical preservatives has been increasingly questioned and restricted. As a biological preservation method, microbial fermentation technology can not only maintain the nutritional value and sensory quality of food, but also produce a variety of natural antibacterial ingredients through microbial metabolic activities, so as to achieve the dual goals of improving food safety and extending shelf-life. The successful application of fermentation technology in traditional foods such as yogurt, pickles and sausage has proved its effectiveness. In recent years, with the rapid development of Microbiology, food science and biotechnology, the application scope of fermentation technology has been expanding and the process parameters have become increasingly accurate, playing an increasingly important role in the modern food industry, providing an innovative path to solve the problem of food safety and quality[1].

2. Food safety and shelf life control mechanism of microbial fermentation technology

2.1. Mechanism of action between organic acids produced by fermentation and antibacterial substances

During fermentation, lactic acid, acetic acid and other organic acids produced by microorganisms metabolizing carbohydrates achieve antibacterial effect through dual mechanisms. Undivided organic acid molecules penetrate the microbial cell membrane by means of fat solubility and dissociate in the cell, releasing protons, leading to cytoplasmic acidification, destroying the proton kinetic potential and inhibiting the activity of key enzymes, so as to collapse the energy metabolism system of pathogenic bacteria and spoilage bacteria. Bacteriocin Produced by lactic acid bacteria, as an antimicrobial peptide synthesized by ribosomes, kills Gram-positive bacteria by forming pores on the target cell membrane or interfering with the synthesis of cell wall. The minimum inhibitory concentration of nisin against Listeria monocytogenes can reach 25 IU/ml. secondary metabolites such as hydrogen peroxide and diacetyl further strengthen the antibacterial barrier. Hydrogen peroxide oxidizes unsaturated fatty acids in the bacterial cell membrane, while diacetyl combines with arginine to block the amino acid metabolic pathway of microorganisms. This multi-target synergy mechanism enables fermented food to establish a more stable microbial control system than a single preservative, which effectively reduces the risk of tolerant strains[2].

2.2. pH adjustment and water activity control mechanism

The changes of environmental parameters caused by fermentation constitute the physical and chemical barrier for food preservation. The accumulation of organic acids reduces the pH value of food from the initial 5.5-6.5 to 4.0-4.5. This acidification process significantly reduces the pH adaptation range of microbial growth, and reduces the growth rate constant of E. coli, Staphylococcus aureus and other moderate preference bacteria by more than 80%. According to Henderson hasselbalch equation, when the environmental pH is less than 1 unit of PKA, the molecular concentration of undivided acid increases by 10 times, and the antibacterial effect increases exponentially. During the fermentation process, the free water content decreases due to the binding water molecules of extracellular polysaccharides synthesized by microorganisms and proteolytic hydrolysates, and the water activity (AW) decreases from 0.98 to 0.92-0.95. The reduction of water activity limits the ability of microorganisms to obtain water for metabolism, prolongs the propagation delay of spoilage bacteria by 3-5 times, and inhibits the deterioration pathways such as lipid oxidation and Maillard reaction. The coordinated regulation of pH and water activity produces a fence effect. Even if a single parameter does not reach the complete antibacterial level, the combined effect of multiple factors can still achieve the goal of long-term preservation (see **Figure 1**).

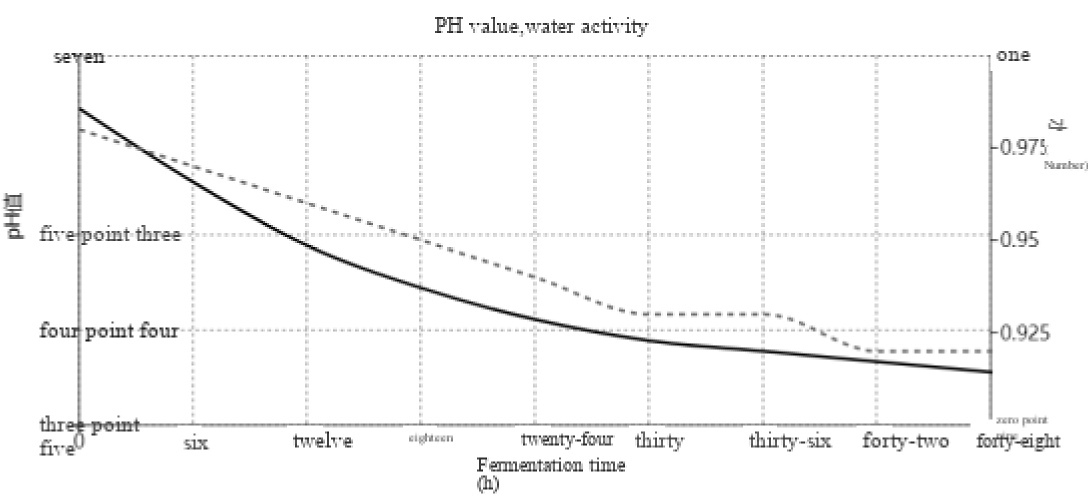

Figure 1. Effect of fermentation time on pH and water activity

Note: the data is based on the model of lactic acid bacteria fermented dairy products, the initial pH is 6.5, and the inoculation volume is 10 μ cfu/ml

2.3. Effect of active metabolites on food quality stability

Fermentation metabolites maintain the long-term stability of food quality by regulating the biochemical reaction kinetics. Protease and peptidase hydrolyze macromolecular proteins into bioactive peptides with molecular weight of 2-5 kDa. These peptides have antioxidant activity, and the thiobarbituric acid value (TBARS) of fermented meat products is maintained below 0.3 mg/kg by scavenging free radicals and chelating metal ions to inhibit lipid peroxidation. Galactose and glucose produced by β - galactosidase decomposing lactose participate in the early stage of Maillard reaction to produce a reducing Amadori compound, which competitively consumes oxygen and interrupts the free radical chain reaction, delaying the fatty acid corruption process. The coenzyme factors such as vitamin B and folic acid synthesized by the fermentation strain maintain the activity balance of the endogenous enzyme system. Glutathione peroxidase continuously removes hydrogen peroxide under the action of coenzyme to prevent its oxidation reaction with unsaturated fatty acids[3]. The extracellular polysaccharides produced by some lactic acid bacteria form a three-dimensional network structure in the food matrix, which physically blocks the diffusion of oxygen to the interior, reducing the oxygen transmission rate by 40-60%. At the same time, the hydroxyl of polysaccharide molecules capture free radicals, cooperate with chemical and physical mechanisms to stabilize the food texture and flavor compounds, and ensure that the rate of sensory quality deterioration during shelf life is controlled within an acceptable range.

3. Research on application effect of fermentation technology in main food types

3.1. Safety improvement and shelf life extension of dairy fermentation technology

Dairy fermentation builds a microbial ecological barrier through the symbiotic metabolism of Streptococcus thermophilus and Lactobacillus bulgaricus. Formic acid and CO α produced by Streptococcus thermophilus provide growth factors for Lactobacillus, while amino acids released by Lactobacillus stimulate the proliferation of Streptococcus[4], making the total number of bacteria reach 10^{8} -10^{9} cfu/ml within 6 hours and occupy the niche quickly. The conversion rate of lactose was more than 90% by fermentation, and the pH value of lactic acid was reduced to 4.2-4.4. Under this acidity condition, the survival time of Escherichia coli o157: h7 was shortened from 72 hours to 8 hours, and the expression of Staphylococcus aureus enterotoxin gene was reduced by more than 95%. The bioactive peptide released by casein enzyme blocked the Fenton reaction by chelating Fe^{2}+ and Cu^{2}+ ions, which prolonged the induction period of lipid peroxidation to 3.2 times that of unfermented milk. The shelf life of fermented yogurt can reach 21-28 days under the storage condition of 4 °C. During this period, hydrogen peroxide continuously produced by lactic acid bacteria maintains the redox potential at+50 to+100 MV, inhibiting the metabolism of aerobic spoilage bacteria. At the same time, the gel network formed by extracellular polysaccharides reduces the rate of whey precipitation, so that the sensory score remains above 8.5 on the 21st day (see **Table 1**).

Table 1. Influence of fermentation on safety index and shelf life of dairy products

Evaluating indicator	Unfermented fresh milk	Fermented yogurt	Improvement range
pH value	6.6-6.8	4.2-4.4	Reduce by 34%
Lactobacilli count (CFU/mL)	<10^{3}	10^{8}-10^{9}	Increase by 10^{5} times
E. coli survival time (h)	72	8	89% shorter
Enterotoxin gene expression	Baseline level	Reduce by 95%	Strong suppression
Lipid peroxidation induction period (days)	3.5	11.2	Extended by 3.2 times
4 shelf life days	7-10	21-28	Extended by 2.5 times
Whey yield	-	<15	Texture stable
Sensory score (21 days)	not applicable, inadequacy, inapplicability	8.5/10	fine quality

3.2. Preservation technology and effect evaluation of fermented meat products

Fermented sausages rely on the co metabolism of Lactobacillus plantarum and Pediococcus pentosaceus to achieve biological preservation. Lactobacillus plantarum converts glucose into lactic acid, acetic acid and CO α through heterotypic fermentation, with an acid production rate of 0.8-1.2 mmol/(L h), rapidly reducing the pH value of mince to below 5.3, and reducing the spore germination rate of Clostridium botulinum from 78% to 12%. Pediocin PA-1 produced by Pediococcus pentosaceus blocked the synthesis of peptidoglycan by binding with lipid II. The bactericidal rate constant of Listeria monocytogenes reached 0.15 h^{-1}, and the colony number decreased by 4 logarithmic orders within 24 hours. During the fermentation process, the endogenous protease hydrolyzed myosin to small molecular peptides, and the content of amino nitrogen increased from 0.3 g/kg to 1.8 g/kg. The sulfhydryl group of free amino acids captured lipid free radicals, reducing the production rate of malondialdehyde by 62%. Under the conditions of fermentation temperature of 22-24 ℃ and relative humidity of 85-90%, the water activity was stable in the range of 0.88-0.90 after 14 days, which inhibited the germination of Aspergillus and Penicillium spores, and the shelf life was extended to more than 90 days. During this period, the volatile basic nitrogen value remained below 15 mg/100g, which met the national standard limit requirements.

3.3. Microbial control and quality maintenance technology of fermented beverages

Fermented beverages achieve microbial stability and flavor balance through the sequential fermentation of yeast and lactic acid bacteria. Yeast converts sucrose into ethanol and CO α in the pre fermentation stage (0-48h). When the ethanol concentration is accumulated to 0.5-2.5% (V/V), the minimum inhibitory concentration against Gram-negative bacteria is 1.2%. At the same time, Co α dissolves to form carbonic acid, which reduces the pH value to 3.8-4.2. This double barrier blocks the growth of Escherichia coli and Salmonella. In the post fermentation stage (48-96 h), lactic acid bacteria used residual monosaccharides to produce lactic acid, the acidity increased from 8 mmolgl to 25-30 mmol/L, the specific growth rate of spoilage bacteria decreased from 0.18 h^{-1} to 0.02 h^{-1}, and the lag period extended to more than 72 hours. The total amount of volatile components such as ethyl acetate and isoamyl alcohol produced by yeast metabolism reached 180-220 mg/L. The hydrolysis rate constant of these flavor compounds in the low pH environment decreased by 40%, and the aroma intensity remained above 85% of the initial value after 60 days of storage. The shelf life of fermented beverages can reach 6 months at room temperature (25 ℃), during which the total acidity fluctuation is less than ± 5%, and the yeast and mold counts are always lower than the detection limit of 10 CFU/ml.

3.4. Application technology optimization of fermented grain and vegetable products

The fermentation of cereal and vegetable broke through the quality fluctuation of traditional natural fermentation through the targeted screening of substrate specific strains. The combination of Lactobacillus acidophilus and Lactobacillus brevis coupled amylase hydrolysis and lactic acid fermentation. The α - amylase activity reached 120-150 U/g, and the conversion rate of reducing sugar produced by hydrolysis exceeded 85%, which increased the yield of organic acids to 55-70 mmol/L, and the pH value was stable in the range of 3.6-4.0. The nitrate reductase system of Lactobacillus plantarum transformed nitrate in vegetables and further reduced it to nitrogen. The nitrite residue decreased from 180 mg/kg to less than 5 mg/kg, eliminating nitrosamine carcinogenic precursors. Ames test verified that the mutation was negative. The cellulase and pectinase released by fermentation degraded cell wall polysaccharides, which increased the soluble dietary fiber from 2.3% to 5.8%, and the bioavailability by 1.5 times. At the same time, the carotenoids and polyphenols released increased the antioxidant capacity to 8500 μ mol TE/100g. Under the conditions of 10 μ CFU/g inoculum and 30-32 ℃ fermentation temperature, the shelf life of fermented cereal and vegetable products can reach 90 days at 4 ℃, the pH fluctuation is less than 0.2 units, and the retention rate of texture hardness is 78%, which provides a technical path for the development of clean label products (see **Table 2**).

Table 2. Changes in functional components of fermented grains and vegetable products

Surveillance Project	Unfermented	Fermented	Change Rate
Starch Hydrolysis Rate (%)	-	85	-
Nitrate (mg/kg)	180	5	-97%
Soluble Dietary Fiber (%)	2.3	5.8	+152%
ORAC Value (µmol TE/100g)	3500	8500	+143%
Shelf Life (days)	15-20	90	+350%

4. Process parameters and effect evaluation of microbial fermentation technology application

4.1. Application characteristics and selection strategies of different fermentation strains

The functional characteristics of fermentation strains determine their suitability in specific food substrates. Lactobacillus plantaricin has become the preferred strain for vegetable fermentation due to its extensive substrate utilization ability and strong acid tolerance. The diameter of the inhibitory zone of its plantaricin bacteriocin against Listeria monocytogenes is 18-22 mm. The homotypic fermentation characteristics of Pediococcus pentosaceus make the lactic acid yield reach the theoretical conversion rate of 95%, which is suitable for meat products requiring rapid acidification. Lactobacillus delbrueckii subsp bulgaricus protein hydrolase activity is up to 350 U/g, which is the key strain for the improvement of the texture of dairy products. The ethanol fermentation efficiency of Saccharomyces cerevisiae is close to the theoretical value, but it is sensitive to so ɑ. So ɑ tolerant Kluyveromyces should be selected for low sulfur drinks. It is necessary to. The selection of strains needs to comprehensively evaluate the acid production rate, antibacterial spectrum, metabolic by-products and environmental tolerance. The synergistic effect can be achieved by optimizing the proportion of multiple strains by response surface methodology[5]. For example, the compound of Lactobacillus plantarum and Pediococcus pentosaceus at 3:1 can increase the pH decline rate of fermented sausage by 40%, and the bacteriocin production increases to 2.3 times that of a single strain.

4.2. Effect of fermentation process conditions on safety and shelf life

The fermentation temperature directly regulated the product safety by affecting the microbial growth kinetics. The specific growth rate of lactic acid bacteria reached the peak value of 0.42 h^{-1} at 37 °C, but the risk of miscellaneous bacteria competition increased. Although the rate of lactic acid bacteria decreased to 0.28 h^{-1} at 30 °C, the growth of Escherichia coli was completely blocked. The amount of seed was linearly correlated with the rate of pH decline, and the time for pH to reach 4.5 was shortened from 12 hours to 4 hours when it was increased from 10^6 to 10^8 CFU/g, and the time for pathogenic bacteria to be exposed to the appropriate environment was reduced by 67%. The salt concentration adjusts the water activity through osmotic pressure. Every 1% increase in salinity within the range of 2-4% will reduce the aw value by 0.015 unit. At the same time, chloride ion inhibits the respiratory chain of Gram-negative bacteria, and the ATP synthesis efficiency will decrease by 55%. The fermentation time needs to balance safety and sensory. When the pH is lower than 3.8 due to excessive fermentation, the sour and astringent taste will burst out, which will reduce consumer acceptance by 40%. The optimal end point should be set in the range of pH 4.0-4.3.

4.3. Comparative analysis of fermentation technology and traditional anti-corrosion methods

The fermentation technology has significant advantages in the continuity of microbial control and consumer acceptance. The inhibition rate of potassium sorbate at 1000 ppm on yeast reached 99%, but the residue decreased to 62% after 30 days, and the inhibition rate decreased to 85%. The fermentation organic acid system maintained a steady state due to the continuous metabolism of microorganisms, and the inhibition effect was stable within 90 days. Sodium benzoate is easy to induce tolerant strains only through a single target inhibition. It has been found that 20% of Escherichia coli is resistant to 500 ppm, while the barrier effect of multiple barriers of fermentation technology reduces the escape probability to 1/15 of chemical corrosion prevention. The direct cost of fermentation process is 0.8-1.2 yuan/kg, which is higher than 0.3-0.5 yuan/kg of chemical preservatives, but the market premium is 30-50%, 68% of consumers accept the price increase of more than 15%. The added value of fermented products such as bioactive peptides and B vitamins significantly affects the competitiveness, and the high-end market share increases from 12% in 2015 to 37% in 2024, which is in line with the development trend of clean labels and functional foods.

5. Epilogue

With its natural, efficient and multifunctional characteristics, microbial fermentation technology has become an important means to improve food safety and extend the shelf life. The active substances such as organic acids and bacteriocins produced in the fermentation process build a multiple microbial barrier, which effectively reduces the risk of foodborne diseases. The successful application in dairy products, meat products, beverages and vegetable foods shows that the collaborative improvement of food safety and sensory quality can be achieved by scientifically selecting fermentation strains and accurately controlling process parameters. Future research should focus on the development of new functional strains, in-depth analysis of fermentation mechanism, intelligent optimization of process parameters and collaborative application of fermentation technology and other preservation technologies, so as to further expand the application scope of fermentation technology.

Disclosure statement

The author declares no conflict of interest.

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