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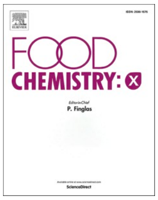

Recent advances of fermented fruits: A review on strains, fermentation strategies, and functional activities

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ABSTRACT

Fruits are recognized as healthy foods with abundant nutritional content. However, due to their high content of sugar and water, they are easily contaminated by microorganisms leading to spoilage. Probiotic fermentation is an effective method to prevent fruit spoilage. In addition, during fermentation, the probiotics can react with the nutrients in fruits to produce new derived compounds, giving the fruit specific flavor, enhanced color, active ingredients, and nutritional values. Noteworthy, the choice of fermentation strains and strategies has a significant impact on the quality of fermented fruits. Thus, this review provides comprehensive information on the fermentation strains (especially yeast, lactic acid bacteria, and acetic acid bacteria), fermentation strategies (natural or inoculation fermentation, mono- or mixed-strain inoculation fermentation, and liquid- or solid-state fermentation), and the effect of fermentation on the shelf life, flavor, color, functional components, and physiological activities of fruits. This review will provide a theoretical guidance for the production of fermented fruits.

1. Introduction

Fruits serve as crucial sources of diverse nutrients, such as dietary fiber, vitamins, and polyphenols, contributing to their status as a healthful food option due to their low fat and calorie content. Studies have shown that regular consumption of fruit could mitigate the risk of various diseases including osteoporosis, diabetes, liver dysfunction, metabolic syndrome, and atherosclerosis caused by poor lifestyle habits (Hasegawa, Kawasaki, Ogawa, Sugiura, & Yano, 2023). However, the richness of nutrients and high moisture content in fruits make them conducive to the proliferation of various microorganisms, particularly parasitic and saprophytic fungi. Fruit deterioration encompasses both pre-harvest and post-harvest stages, with post-harvest microbiological contamination emerging as the main cause of fruit deterioration. At the post-harvest stage, the nutrients in the fruit provide a favorable environment for the growth of microorganisms, particularly yeasts and molds (Zhao, Ndayambaje, Liu, & Xia, 2022). This susceptibility to spoilage not only leads to substantial economic losses but also gives rise to the production of toxins, posing a significant threat to consumer health. For example, patulin, a prevalent fruit toxin produced by *Penicillium* and *Aspergillus*, has been identified for its potential to inflict harm to several organs, including the kidneys (Hou et al., 2022) and liver (Zhang et al., 2022). Hence, the exploration of strategies to mitigate fruit spoilage is of utmost importance.

Proper fruit processing is a good solution to the problem of perishable fruit. However, conventional methods like quick-freezing and blanching have been found to significantly diminish the nutritional content of fruits. In recent years, probiotic fermentation has become an effective way to counteract fruit spoilage due to it can not only extend the shelf life of fruits by inhibiting the proliferation of harmful bacteria but also enhances the flavor and preserves the beneficial substances (Muhialdin, Kadum, Zarei, & Hussin, 2020; Sevindik et al., 2022; Wang et al., 2023). Notably, fermentation stands out as a cost-effective and energy-efficient process.

Fermented fruits are produced by the intricate interaction of microorganisms with the natural fruit medium rich in glucose and fructose. This process facilitates easy storage and transportation, and has witnessed a recent surge in development. Recently, various beneficial microorganisms, such as yeast (Velenosi et al., 2021), *Lactobacillus* (Meng et al., 2022), and *Acetobacter* (Paz-Arteaga et al., 2023), have played a pivotal role in the rapid evolution of fermented products derived from fresh fruits and their by-products. Fermentation contributes greatly to

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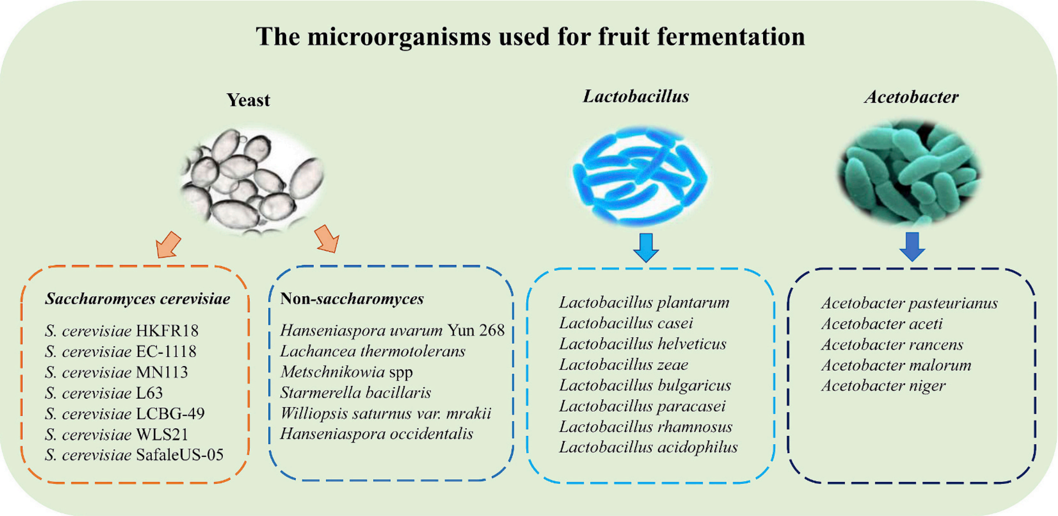

Fig. 1. The strains used for fruit fermentation including *Saccharomyces cerevisiae*, non-*saccharomyces*, *Lactobacillus,* and *Acetobacter*.

the functional activity of the fruits. On the one hand, microorganisms in fermented products could regulate gut microbiota and produce beneficial microbial metabolites such as organic acids (e.g., short-chain fatty acid and gamma-aminobutyric acid) (Ma et al., 2021). On the other hand, fermentation can increase the content of functional nutrients of fruits including polyphenols, flavonoids, organic acids, polysaccharides, amino acids, vitamins, minerals, and other efficacious components, giving the fruit excellent antioxidant, antibacterial, anti-inflammatory, and gut microbiota modulation activities (Feng, Wu, & Weng, 2022; Sheng et al., 2021). Moreover, microbial fermentation can impart distinctive fruity and floral aromas to fruits through the production of esters, ketones, alcohols, terpenes, etc. (Sevindik et al., 2022).

The choice of strains and fermentation strategies emerges as crucial determinants impacting the overall quality of fermented products. These factors play a pivotal role not only in ensuring fermentation uniformity but also in influencing the safety, flavors, and nutritional profiles of the end products. In order to provide a theoretical reference to the development of fermented fruits, this review summarized the commonly used microorganisms and their fermentation strategies in fruit fermentation. Additionally, the review delves into the multifaceted effects of microbial fermentation on the nutritional value, flavor, color, and shelf life of fermented fruit products.

2. Strains used for fruit fermentation

Fruit fermentation refers to the fermentation of one or more fresh fruits under the action of single or composite strains for a certain period. Typically, strains such as lactic acid bacteria, acetic acid bacteria, and yeasts are employed in fruit fermentation, which play a pivotal role in converting sugars present in fruits into alcohol, acetic acid, lactic acid, and other bioactive components, including polyphenols and bioactive peptides, endowing the fruits with distinctive flavor and nutritional values (Fig. 1).

2.1. Yeast

Yeasts are a group of unicellular eukaryotic organisms, which are widely used in the production of fruit wines, fruit enzymes, jams, and more. Throughout the fermentation process, yeasts play a pivotal role in converting the glucose and fructose present in fruits into alcohol and carbon dioxide. Simultaneously, vitamins, amino acids, and other beneficial metabolites were produced. *Saccharomyces cerevisiae* are the most used strains in fruit wine fermentation. Currently, the specialized commercial strains of *Saccharomyces cerevisiae* employed in fruit wine fermentation mainly include *Saccharomyces cerevisiae* HKFR18 (Baek, Kim, Park, Son Jong, & Shim Jae, 2021), *Saccharomyces cerevisiae* EC-1118 (Jiang, Lu, & Liu, 2020), *Saccharomyces cerevisiae* MN113 (Francesca et al., 2023), *Saccharomyces cerevisiae* L63 (Andrade Koelher, de Souza, da Costa, & Aguiar-Oliveira, 2022), *Saccharomyces cerevisiae* LCBG-49 (Edward-Rajanayagam et al., 2023), *Saccharomyces cerevisiae* WLS21 (Li et al., 2022), *Saccharomyces cerevisiae* SafaleUS-05 (Cioch-Skoneczny, Krolak, Tworzydlo, Satora, & Skoneczny, 2023), etc. In recent years, to overcome the drawback of single and convergence flavor caused by commercial *Saccharomyces cerevisiae*, there has been a growing trend to isolate and cultivate more unique *Saccharomyces cerevisiae* from typical fermented foodstuffs using natural and industrial screening methods. Moreover, to generate more aroma compounds, non-*saccharomyces* received increasing attention, which plays an indispensable role in fruit wine fermentation. Compared to *Saccharomyces cerevisiae*, non-*saccharomyces* exhibit higher extracellular enzyme activity, which could hydrolyze more aroma precursors to release abundant aroma substances, thus giving complex aromas to fruit wines (Renault, Coulon, de Revel, Barbe, & Bely, 2015). Concurrently, certain non-*saccharomyces* can produce more complex metabolites (e.g., esters, higher alcohols, and glycerol) to reduce alcohol content. The synergistic fermentation with non-*saccharomyces* and *Saccharomyces cerevisiae* was increasingly used in fruit wine production, which could produce superior flavor. For example, a study by Hu, Jin, Xu, and Tao (2018) demonstrated that collaborative fermentation with *Hanseniaspora uvarum* Yun 268 and *Saccharomyces cerevisiae* increased the production of medium-chain fatty acid ethyl esters in wines, imparting a unique flavor. Another study conducted by Binati et al. (2020) suggested that sequential inoculation of specifically selected strains (*Lachancea thermotolerans, Metschnikowia* spp. and *Starmerella bacillaris*) and *Saccharomyces cerevisiae* EC 1118 positively modulated some relevant chemical parameters and improved the aromatic intensity of wine by increasing the levels of lactic acid, higher alcohols, esters, and glycerol, while reducing ethanol, acetaldehyde, SO_2, and volatile phenols contents. Beyond flavor enhancement, some beneficial compounds (e.g., melatonin) can be produced by non-*saccharomyces*, improving the nutritional value of the fruit wines (Capece et al., 2018).

2.2. Lactic acid bacteria

Lactic acid bacteria are a group of gram-positive bacteria that can ferment sugars to produce lactic acid, which are widely distributed in nature, mainly in fermented foods (such as yogurt), intestinal tracts of animals, soil, water, etc. Lactic acid bacteria play a crucial role in fruit

Fig. 2. The fruit fermentation method including natural fermentation, inoculation fermentation, mono-strain inoculation fermentation, mixed-strain inoculation fermentation, lipid-state fermentation, and solid-state fermentation.

fermentation by utilizing carbon sources and free amino acids to produce abundant metabolites including organic acids, bioactive peptides, fatty acids, extracellular polysaccharides, vitamins, etc. The fermentation process of lactic acid bacteria encompasses glycolysis and other alternative pathways. Glycolysis is a process of converting sugar molecules to lactic acid, ethanol, carbon dioxide, etc. Under anaerobic conditions, lactic acid bacteria generate energy through lactic acid fermentation. Simultaneously, lactic acid and other organic acids were produced, which could lower the pH of the environment, discourage the growth of harmful microorganisms, and give fermented fruits special flavor and texture. *Lactobacillus plantarum* (Zhao et al., 2021), *Lactobacillus casei* (Bancalari, Castellone, Bottari, & Gatti, 2020), *Lactobacillus helveticus* (Bancalari et al., 2020), *Lactobacillus zeae* (Inayah, Wibowo, Julianti, & Suciati, 2022), *Lactobacillus bulgaricus* (Oberg, McMahon, Culumber, McAuliffe, & Oberg, 2022), *Lactobacillus paracasei* (Garcia et al., 2018), *Lactobacillus rhamnosus* (Lu, Tan, Chen, & Liu, 2018), and *Lactobacillus acidophilus* (da Silva et al., 2021) are the commonly used *Lactobacilli* in fruit fermentation. Although different *Lactobacilli* play different roles in the fermentation process, their main roles include producing beneficial metabolites such as lactic acid, vitamins, amino acids, polyphenols, etc., lowering the pH value of products to inhibit the growth of harmful microorganisms, prolonging the shelf-life, and improving the texture. For example, a study conducted by Hashemi et al. (2017) showed that the amount of *L. plantarum* LS5 in sweet lemon juice increased from 7.0 ± 0.1 CFU/mL to 8.63 ± 0.38 CFU/mL after 48 h of fermentation, and furthermore, the amount of lactic acid and antioxidant actives (e.g., ascorbic acid) after fermentation also increased significantly, while exhibiting higher antimicrobial properties and antioxidant activity, making it a potential candidate for non-dairy functional beverages. In addition, Kaprasob, Kerdchoechuen, Laohakunjit, and Somboonpanyakul (2018) indicated that cashew apple juice fermented by *L. plantarum*, *L. casei*, and *L. acidophilus* at 30 °C for 48 h increased bioactive substances including concentrated tannins, vitamin C, and phenolic metabolites.

2.3. Acetic acid bacteria

Acetic acid bacteria play a crucial role in the production of fruit vinegar, primarily generating acetic acid and imparting flavor throughout the process. Acetic acid bacteria fermentation involves the oxidation of ethanol to acetic acid and can be categorized into one-step method (simultaneous addition of alcohol and *Acetobacter*) and two-step process (introduction of *Acetobacter* after yeast-mediated alcohol fermentation). Generally, fruit vinegar produced by one-step have better quality such as more diverse flavor, more abundant functional components, and higher fermentation efficiency. Therefore, acetic acid bacteria utilized in fruit vinegar fermentation should have certain ethanol and high-temperature resistance. The screening of high acid-producing acetic acid bacteria with alcohol and temperature tolerance is of great significance in improving the quality of fermented fruit vinegar.

Researchers have striving to isolate high-performing acetic acid bacteria from vinegar grains, vinegar mash, and decay sites of fruits. Recently, *Acetobacter pasteurianus* (Wu et al., 2018), *Acetobacter aceti* (Sombolestani et al., 2020), *Acetobacter rancens* (Zheng, Liu, Zhang, & Wang, 2010), and *Acetobacter malorum* (Sainz, Mas, & Torija, 2017) stand out as the most frequently employed strains in fruit vinegar fermentation. These *Acetobacter* strains demonstrated the ability to convert alcohol into acetic acid, meanwhile, some volatile aroma components such as organic acids, esters, ketones, and aldehydes were produced, giving fruit vinegar complex aroma and flavor. For example, Xu et al. (2022) showed that coconut water vinegar fermented by active *Acetobacter* exhibited elevated levels of phenyl acetate, isoamyl acetate, and benzaldehyde, imparting an almond, banana, and pear aroma to the coconut water vinegar. In addition, fermented coconut water vinegar contains essential amino acids, especially phenylalanine. Additionally, *Acetobacter* fermentation contributes to the production of antioxidant components such as polyphenols. For instance, pineapple beer vinegar fermented by *Saccharomyces cerevisiae* (LAS01) and *Acetobacter* sp. (ASV03) exhibited higher levels of polyphenols and antioxidant actives (Sossou, Ameyapoh, Karou, & de Souza, 2009). Despite the discovery and application of various *Acetobacter* strains in fruit vinegar fermentation, limited information exists regarding the impact of different *Acetobacter* strains on the quality of the same fruit vinegar. This will be a topic for future research to increase the variety of commercially available fruit vinegars.

2.4. *Other strains*

Except for the yeast, Lactic acid bacteria, and Acetic acid bacteria, *Leuconostoc mesenteroides* have emerged as a valuable candidate for fruit fermentation. Recently, *Leuconostoc mesenteroides* has been successfully employed in the fermentation of prickly pear. It could enhance the radical-scavenging and antibacterial activities of prickly pear juice (Lee et al., 2016). Moreover, *Leuconostoc mesenteroides* fermentation has the potential to extend the shelf life and improve the rheological, sensory, and functional features of prickly pear fruit puree (Di Cagno et al., 2016). In addition, some *Aspergillus,* especially *Aspergillus oryzae* (Khandelwal, Srivastava, & Bisaria, 2023), *Aspergillus niger* (Saad et al., 2023), and *Aspergillus kawachii* (Miyamoto et al., 2020) were used to ferment the byproducts of fruit, including peel, pomace, and stone using the solid-state method. This approach yields a diverse array of enzymes (e.g., amylase, polygalacturonase, and pectinase) and organic acids (e.g., citric acid, gluconic acid, and gallic acid).

Noteablely, vegetables and fruits contain many common nutrients such as vitamins, minerals, dietary fiber, etc. Differently, vegetables usually contain more dietary fiber and minerals, while fruits contain more sugars and vitamins. Thus, vegetables are more used to make pickled cabbage, salted vegetables, and fermented vegetable juice. The strains suitable for fruit fermentation can also be used for vegetable fermentation, especially lactic acid bacteria and yeast.

Altogether, microorganisms significantly affect the quality of fermented fruits. Nevertheless, the quality of fruits fermented by microorganisms is not only related to fermentation strains but also influenced by fermentation parameters, especially fermentation strategies.

3. Fruit fermentation strategies

According to different division forms, the common methods used for fruit fermentation mainly divided into natural and inoculation fermentation as well as solid- and liquid-state fermentation. Different fermentation methods not only have different applicability but also have a great impact on the quality of the fermented product (Fig. 2).

3.1. *The form of fermentation*

3.1.1. *Natural fermentation*

Natural fermentation is a process of using microorganisms from natural environment. Yeast is the first microorganism discovered during the natural fermentation process of bread. Subsequently, *Lactobacillus* and *Acetobacter* were gradually discovered in yogurt and kimchi. With the development of food industry, natural fermentation has been used to produce kiwi wine, persimmon fruit vinegar, and fermented strawberry juice. Generally, compared with inoculation fermentation, natural fermentation can yield a more diverse and distinctive array of flavor compounds. For example, the levels of carboxylic acid, aldehydes, ketones, and phenolic aroma components of natural fermented persimmon vinegar were higher than those by inoculated fermentation (Lu, Zheng, Zhao, & Bai, 2009). Although natural fermentation is a widely used traditional technique, it still has many drawbacks that limit its development as follows: 1) fermentation strains are unknown; 2) spoilage organisms and stray bacteria are easily introduced; 3) fermentation is difficult to start; 4) fermentation is easily aborted; 5) fermentation result is not controllable; 6) heterohydric alcohols, highly volatile acids, and other hazardous substances are easily produced.

3.1.2. *Inoculation fermentation*

Inoculation fermentation is a process that introduces specific microbial strains into products to be fermented, which presents several advantages over natural fermentation, such as better control of fermentation time, rate, and quality, consistency and predictability of the product, and the avoidance of harmful microorganisms.

Microorganisms suitable for inoculation fermentation include endogenous and commercial strains. Endogenous strains refer to the microorganisms isolated from raw materials, offering distinct advantages such as 1) strong adaptability to the fermentation environment; 2) higher nutritional value of their fermented juice. However, the process of screening specific endogenous strains suitable for fermentation is more complicated and demands a longer experimental period. Yim and Boong (2015) screened acid-, alcohol- and sulfide-resistant *Bartonella* spp. SCMA5 and SCMA6 from traditional fermented foods with the ability to produce large amounts of acetic acid. These strains were found to enhance the antioxidant and hypoglycemic activities of fermented mulberry fruit vinegar. Kanklai, Somwong, Rungsirivanich, and Thongwai (2021) isolated a γ-aminobutyric acid-producing strain, named *Levilactobacillus brevis* F064A, from Thai fermented sausages, and used it to ferment mulberry juice, which significantly increased the contents of antioxidants such as γ-aminobutyric acid and anthocyanins. Ueda et al. (2016) isolated an *L. plantarum* BFRI 380–7 from persimmons and employed it for the fermentation of persimmon syrup, producing a fermented lactic acid drink without milk components.

Commercial strains are specific colonies of microorganisms commonly used to accelerate, control, and improve the fermentation process of beverages and other products. These strains undergo careful screening, cultivation, and propagation to ensure consistent activity and efficacy in specific environments. Currently, the primary commercial strains used for fruit fermentation include *Lactobacillus* such as *L. plantarum*, *L. casei*, *L. acidophilus*, and *Lactobacillus suis*, yeasts such as yeasts UNICAMP-V1, yeasts QA23, yeasts Elegance MP061, yeasts M05 Mead, and *Acetobacters* such as *A. aceti*, *Acetobacter schutzenbachii*, and *A. pasteurianus*. These commercial strains are commonly used to produce fruit fermentation products through mono-or mixed-strain inoculation fermentation.

3.2. *The methods of strain inoculation*

3.2.1. *Mono-strain inoculation*

Inoculation fermentation is further categorized into mono-and mixed-strain inoculation fermentation. The process of inoculating a single pure strain to transform substrate is named mono-strain inoculation fermentation. This approach could significantly reduce fermentation time and is particularly favorable for industrial production. However, products fermented with a mono-strain may be somewhat lacking in flavor depth. Mixed-strain fermentation can compensate for

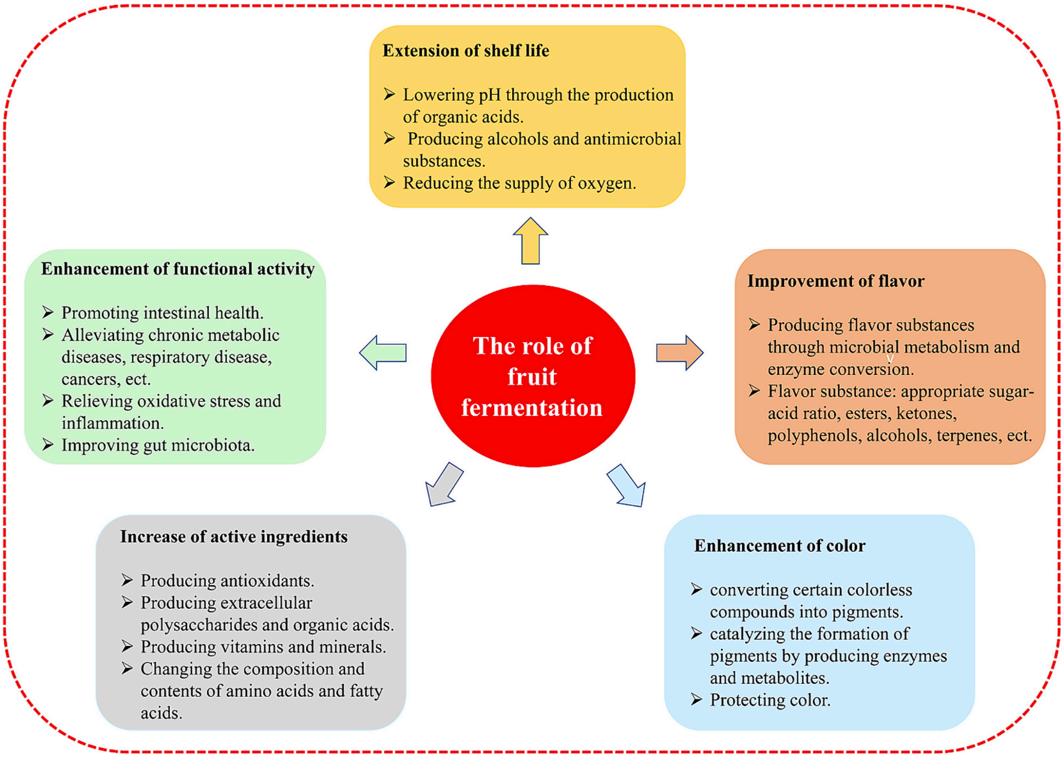

Fig. 3. The beneficial effects of fruit fermentation including the extension of shelf life, the improvement of flavor, the enhancement of color, the increase of active ingredients, and the enhancement of functional activities.

this shortcoming.

3.2.2. *Mixed-strain inoculation*

In mixed-strain fermentation, several different species are utilized to create a more intricate transformation process, leading to the generation of a product with a more complex flavor profile. Li et al. (2017) conducted a study comparing the impact of mono- and mixed-strain inoculation fermentation (utilizing *L. paracasei* 20241, *Bifidobacterium animalis* 6165, *Streptococcus thermophilus* 6063, and *L. acidophilus* 6005) on the quality of apple juice. The results revealed that the contents of alcohols, esters, and other aroma substances were significantly higher than that of mono-strain fermentation, which conferred a stronger fruity and floral flavor. Another study conducted by Sheng et al. (2022) evaluated the effect of mono-and mixed-strain inoculation fermentation with *L. acidophilus* 26 and *L. plantarum* 56 on the quality of red globe grape juice. The results indicated that mixed-strain inoculation fermentation exhibited superior viable bacteria count, total soluble solids, and antioxidant properties compared to mono-strain fermentation. Furthermore, the contents of flavor substances such as lactic acid, acetic acid, ethyl acetate, ethyl benzoate, sorbic acid, and 2-hexenol were significantly increased in the mixed-strain inoculation fermentation. Moreover, when a species produces specific metabolites that contribute to the growth of another species, they may undergo synergistic metabolism (Frey-Klett et al., 2011). It is worth noting that mixed-strain fermentation involves complex interactions of multiple strains and requires more careful control and regulation.

3.3. *The state of fermentation system*

3.3.1. *Liquid-state*

Depending on the state of the medium, fermentation is further categorized into liquid- and solid-state fermentation. Liquid-state fermentation is the primary method employed for large-scale industrial production due to its consistency and ease of control (e.g., temperature, pH, aseptic conditions, and oxygen supply). This method is commonly used in the production of enzymes, fruit wines, and fruit vinegars.

3.3.2. *Solid-state*

Solid-state fermentation is typically applied to ferment the by-products of fruits, such as pineapple pomace, apple pomace, grape pomace, bagasse, citrus rind, pomegranate seeds, mango peel, and banana peel to achieve their high-value utilization. Compared to liquid-state fermentation, solid-state fermentation offers several advantages including high product concentration, low pressure, low energy consumption, and relatively simple equipment. Moreover, solid-state fermentation can enrich and produce some special functional substances. A study has indicated that the enzyme titers in solid-state fermentation are higher than those in deep-liquid fermentation (Roy, Dutta, Sarkar, & Ghosh, 2013). Saeed, Shahid, Naseer, Ghazanfar, and Irfan (2023) achieved the highest fructose yield (7.586 mg/g) through solid-state fermentation of sucrose-rich mango peels using *Bacillus subtilis* at 32 °C, 60% moisture, and pH 7 for 120 h. Aslam et al. (2020) obtained maximum pectinase yield by solid-state fermentation of data palm waste with *Bacillus licheniformis* KIBGE-IB3 at 37 °C and pH 7.0 for 72 h. However, solid-state fermentation has some limitations, as the incubation time is longer than liquid fermentation and the productivity tends to be lower. Moreover, solid-state fermentation is susceptible to contamination by stray bacteria. Despite these limitations, the unique advantages make solid-state fermentation a valuable approach for certain applications, especially in the utilization of fruit by-products.

While various fermentation methods come with distinct targets and associated advantages and disadvantages, they universally contribute to enhancing the sensory characteristics, nutritional value, and storage stability of fruits to a certain extent. Next, the focus of our review will shift to introducing the beneficial effect of fermentation.

4. The beneficial effect of fruit fermentation

Fruit fermentation is a biochemical process where microorganisms

Table 1
Effects of fermentation on shelf life and color of fruits.

Fruits	Strain	Strain source	Fermentation method	Flavor Improvement	Reference
Dragon fruit	*L. plantarum* FBS05	Isolated from fermented traditional Malaysian food	Inoculation fermentation	Enhanced antibacterial activity for dragon fruit juice approximately by three folds; Decreased microbial load and extended shelf life of fresh dragon fruit juice for 3 months at 8 °C after adding 10% fermented dragon juice	(Muhialdin et al., 2020)
Cantaloupe	*L. plantarum* FBS05	Isolated from tempeh (fermented soybean curd)	Inoculation fermentation	Inhibited *E. coli*, *Salmonella typhimurium*, *Aspergillus flavus*, and *Penicillium spp*; Extended the shelf life of fresh cantaloupe juice by 6 months with the addition of 20% fermented cantaloupe juice	(Muhialdin, Kadum, & Hussin, 2021)
Strawberry, grape, and acerola extracts	Traditional water kefir grains	Donated by artisan producers from Maringá, in the state of Paraná, Brazil	Inoculation fermentation	Exhibited antimicrobial potential against *Alicyclobacillus*	(de Menezes et al., 2022)
Sweet lemon juice (*Citrus limetta*)	*L. plantarum* LS5	Obtained from the strain collection of Ferdowsi University of Mashhad, Iran	Inoculation fermentation	Increased antibacterial activity; Against *Salmonella Typhimurium* ATCC 14028 and *E. coli* O157:H7 ATCC 35150	(Hashemi et al., 2017)
Blueberry (*Vaccinium corymbosum* L)	*Bacillus amyloliquefaciens*; *L. brevis*; *Starmerella bombicola*	Isolated from fermented starfish	Mono-strain inoculation fermentation	*Bacillus amyloliquefaciens* and *Starmerella bombicola* enhanced the antimicrobial activity of skin bacteria	(Oh, Jeong, Velmurugan, Park, & Jeong, 2017)
Chagalapoli fruit	*S. cerevisiae* yeast	Purchased from Red Star brand	Mono-strain inoculation fermentation	Increased L^*, indicating the samples are darker; Decreased a^*, indicating a red tone; Increased b^*, obtaining a yellow color	(Flores-Garcia et al., 2019)
Orange (*Citrus sinensis*), tangerine (*Citrus reticulata*), grapefruit (Citrus paradisi)	*Lactic acid bacteria*	Isolated from dairy products (yogurt, cheese, and butter samples)	Mono-strain inoculation fermentation	Increased antibacterial activity, especially for Gram (−) bacteria and fungus; Increased titration acidity, free radical scavenging activity, and total phenolic substance values; Decreased pH, aw, dry matter, viscosity, brix, and L* values	(Akarca & Baytal, 2023)
Apple	*L. acidophilus* BNCC 185342, *L. casei* ATCC 393, *L. plantarum* BNCC 337796	Obtained from Beijing Beina Chuanglian Biotechnology Research Institute (Beijing, China)	Mono-strain inoculation fermentation	Decreased pH; Inhibited *E. coli* and *Staphylococcus aureus*	(Yang et al., 2022)
Mulberry	*Levilactobacillus brevis* F064A	Isolated from Thai fermented sausage	Inoculation fermentation	Inhibited the growth of *Bacillus cereus* TISTR 687, *Salmonella enterica subspecies enterica serovar Typhi* DMST 22842, and *Shigella dysenteriae* DMST 1511	(Kanklai et al., 2021)
Date fruit (*Khastawi*)	*L. plantarum* ATCC 8014	Not mentioned	Inoculation fermentation	Inhibited *Aspergillus niger*, *Aspergillus flavus, Escherichia coli,* and *Staphylococcus aureus*; Extended the shelf life of Dodol	(Muhialdin, Kadum, & Hussin, 2021; Muhialdin, Marzlan, et al., 2021)
Strawberry	LAB (*L. plantarum, L. bulgaricus)* and yeast (*S. cerevisiae*)	Obtained from Sichuan Food Fermentation Industry Research and Design Institute, Chengdu City, Sichuan Province, China	Inoculation fermentation	Inhibited *Escherichia coli* ATCC 25922, *Staphylococcus aureus* ATCC 6538, *Pseudomonas aeruginosa* ATCC 9027, and *Bacillus subtilis* ATCC6633; Inhibited the biofilm formation of *Escherichia coli* ATCC 25922 and *Staphylococcus aureus* ATCC 6538	(Zhao, Lan, et al., 2021)
Blueberry	Self-made starters (*L. plantarum, L. acidophilus, L. paracasei, L. rhamnosus, L. acidipiscis, S. cerevisiae*); Commercial starters (*Bacillus coagulans, L. plantarum, S. cerevisiae*)	Commercial starters were from Zhejiang Quanzhi Biotechnology Co. Ltd. (Hangzhou, China)	Natural fermentation; Inoculation fermentation of self-made starters and commercial starters	Inhibited the growth of *Escherichia coli*, *Staphylococcus aureus*, and *Salmonella Typhimurium*	(Zhong, Abdullah, & M., Tang, J., Deng, L., & Feng, F., 2021)
Grape	*Oenococcus oeni* MS9 and MS46	Isolated from wine collected from a cellar from Cafayate, Salta, Argentina	Mono-strain inoculation fermentation	Inhibited the activity of *Escherichia coli* 700, *Salmonella Typhimurium*, and *Listeria monocytogenes*	(del Valle, Carmen, Jose, & Maria, 2022)
Mixed fruit juice (pineapple, winter melon, longanhone)	*L. plantarum* TISTR 1465; *L. salivarius* TISTR 1112; *Starmerella boulardii* CNCM I-745	Obtained from the Thailand Institute of Scientific and Technological Research	Mono-or mixed-strain inoculation fermentation	Against *Salmonella Typhi* DMST 22842; Inhibited the formation of Biofilm	(Laosee, Kantachote, Chansuwan, & Sirinupong, 2022)
Grape	*S. cerevisiae* (SCE16 and SCE138); *Starmerella bacillaris* (FA18)	The two *S. cerevisiae* were isolated from 'Savigninin Jura'; *Starmerella bacillaris* was isolated from 'Pinot noir' in Burgundy	Sequential inoculation fermentation	Promoted the evolution of wine color and stabilize it	(Velenosi et al., 2021)

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Table 1 (*continued*)

Fruits	Strain	Strain source	Fermentation method	Flavor Improvement	Reference
Grape	*L. plantarum* Lp39 (CICC6240) and C8–1 (CICC23138); *O. oeni* strains (Viniflora® Oenos and CiNe)	*L. plantarum* Lp39 were received from the China Center of Industrial Culture Collection (Beijing, China); *O. oeni* strains were purchased from Chr. Hansen (Hoersholmm, Denmark)	Mono-strain inoculation fermentation	*L. plantarum* promoted the formation of acetaldehyde during malolactic fermentation; Increased the content of pyranoanthocyanins;	(Wang et al., 2018)
Pineapple residues	*A. niger* GH1 (MUM:23.16)	Obtained from the DIA-UAdeC collection and deposited in the Micoteca of the University of Minho	Solid-state fermentation	Against *Staphylococcus aureus* and *Listeria monocytogenes*	(Paz-Arteaga et al., 2023)

L. brevis, Lactobacillus brevis; *L. acidipiscis, Lactobacillus acidipiscis*; *L. salivarius, Lactobacillus salivarius*; *A. niger, Acetobacter niger.*

(typically bacteria and yeast) transform carbohydrates in fruits into products such as organic acids, alcohols, and gases. This fermentation process plays several essential roles mainly including the extension of shelf-life, the production of flavor and aroma, the enhancement of color, the increase of active ingredients, and the maintenance of health (Fig. 3).

4.1. Extension of shelf life

Fruits, being high in water and nutrients, are prone to microbial attack, especially considering the diverse microorganisms present on their surfaces. In addition, the thin and easily broken skin of some fruits exacerbates the risk of spoilage. Microbial fermentation serves as an effective means to extend the shelf life of fruits. It can inhibit the growth of harmful microorganisms by 1) lowering the pH through the production of organic acids; 2) producing alcohols and some antimicrobial substances such as organic acid, antimicrobial enzyme, and peptide; 3) reducing the supply of oxygen through the production of gases such as carbon dioxide (Table 1). A study conducted by Di Cagno et al. (2008) showed that the use of selected indigenous *Lactobacillus* fermenters extended the shelf life of fermented tomato juice, pineapple fruits, and cherry puree, while maintaining the satisfactory nutritional, rheological, and organoleptic properties of these fruits. Muhialdin et al. (2020) showed that the pH of *L. plantarum* FBS05 fermented dragon fruit juice was reduced from 5.61 to 3.49, which significantly inhibited the growth of *Escherichia coli*, *Salmonella Typhimurium*, *Pseudomonas aeruginosa*, and *Staphylococcus aureus*. And supplementation of 10% fermented dragon fruit juice extended the shelf life of fresh dragon fruit juice by 3 months. Similar results were obtained in another study conducted by Muhialdin, Kadum, and Hussin (2021). Adding 20% of fermented cantaloupe juice by *L. plantarum* FBS05 extended the shelf life of fresh cantaloupe juice by 6 months when stored at 8 °C. Thus, fermentation is an effective method to extend the shelf life of fruits.

4.2. Improvement of flavor

As the standard of living improves, the pursuit of flavor becomes increasingly passionate. The content and composition of flavor substances in fermented foods play a crucial role in determining their final organoleptic quality and overall product acceptance (Cai et al., 2021). Microbial growth, metabolism, and enzyme-producing capacity are pivotal factors influencing the formation of flavors in fermented foods. In fruits, many aroma precursors such as sugars, glycosides, and amino acids are present, which typically lack distinctive aroma properties. However, through a series of biochemical reactions involving microorganisms and their enzymes (e.g., pectinases, glycosidases, proteases, and lipases), these precursors can be converted into complex aroma compounds, contributing to the development of rich and diverse flavors. In addition, due to the different nutritional components of fruits and the fermentation characteristics of strains employed, the content of organic acids, reducing sugars, and volatile flavor components in the fermented juice is different. In general, sugars, acids, and amino acids serve as the key aromatic compounds in fermented fruit juices, and the appropriate sugar-acid ratio gives the fermented product a moderately sweet and sour taste. Esters, ketones, and phenolics give the fermented fruits sweet and fruity flavor. Alcohols, ketones, and terpenes are associated with the floral and fruity aromas of the fermented fruits. Thus, microorganisms and their metabolic transformation are essential for the flavor presentation of fermented fruit products. Chen, Lu, Yu, Chen, and Tian (2019) found that fermented apple juice produced by *Lactobacillus* contained various flavor substances such as ketones (e.g., 4-heptanone, 2-nonanone, and 4-cyclopentene-1,3-dione), acetaldehyde, esters, and alcohols, improving the final flavor of the product. The study of Di Cagno, Filannino, and Gobbetti (2017) showed that *Lactobacillus* fermentation of pomegranate juice produced well-flavored substances including alcohols, ketones, olefins, and terpenes, while, reduced aldehydes with off-flavors. Ricci et al. (2018) used the strains of *L. plantarum* and *L. rhamnosus* isolated from dairy products and plant substrates for the fermentation of elderberry juice. The results showed that ethyl acetate, methyl isovalerate, isoamyl isovalerate, and methyl salicylate contents increased greatly, which were associated with fruit odor. The specific effects of fermentation on fruit flavor are shown in Table 2.

4.3. Enhancement of color

The color stands out as a pivotal determinant of fermented fruit quality, intricately intertwined with flavor, safety, and nutritional value. Good color has a positive impact on the fermented fruit quality, which can not only enhance its visual appeal but also endow fermented fruits with stronger biological activities by producing natural pigments (e.g., carotenoids, anthocyanins, flavonoids). Raw material pigments, fermentation strain, enzyme, and metabolites produced by microorganisms are important influencing factors for the color formation of fermented fruits. Fruits' inherent pigments precursor serve as substrates for color development, and microorganisms play a transformative role by converting certain colorless compounds into pigments through a series of reactions. For example, colorless flavanols present in grapes and wine are actively involved in oxidative browning, engaging in reactions with anthocyanins to give rise to derived pigments (Lambert et al., 2015). Moreover, enzymes and metabolites produced by fermentation strains can act as catalysts to accelerate the formation of pigments. For example, Acetaldehyde released by *L. plantarum* enhanced the formation of pyran anthocyanins in wine during malolactic fermentation (Wang et al., 2018). In addition, some strains can assist in color retention. For example, various non-*saccharomyces* have a protective effect on wine color, such as *Starmerella bacillis* (Velenosi et al., 2021). Therefore, fermentation is a great method to improve color (Table 1).

4.4. Increase of active ingredients

The widespread appeal of fermented foods can be attributed, in part, to their rich concentration of active ingredients, imparting health

Table 2
Effect of fermentation on the flavor of fruits.

Fruits	Strain	Strain source	Fermentation method	Flavor improvement	Reference
Grape	*S. bayanus* Y4, *Torulaspora delbrueckii* Y7	Isolated from the mash of the fruit wine factory (Chengdu, China)	Mono-or mixed-strain inoculation fermentation	Reduced total acidity and dominant organic acids; Decreased aliphatic compounds; Increased aromatic compounds including acetate esters, ketones, and terpenes	(Liu et al., 2023)
Longan	*W. saturnus* ssp. *saturnus* CBS 254	From CBS Culture Collections (The Netherlands)	Inoculation fermentation	Enhanced the production of isoamyl alcohol and its ester, isoamyl acetate, 2-phenylethanolandits ester, and 2-phenylethylacetate	(Thi-Thanh-Tam, Yu, Curran, & Liu, 2012)
Noni fruit	*Acetobacter* sp. (GDMCC *No.*62221)	Isolated from naturally fermented noni juice	Inoculation fermentation	Decreased or even eliminated hexanoic acid, octanoic acid, and butanoic acid	(Zhang et al., 2023; Zhang et al., 2023; Zhang et al., 2023)
Apricot Juice	*L. plantarum* (LP56)	Obtained from Xiannong Biotechnology (Shanghai) Co. Ltd	Inoculation fermentation	Increased alcohols, aldehyde, acid, and ester, giving fruits pine and citrus flavors	(Sun et al., 2022)
Grewia berries and cantaloupe	*S. cerevisiae* NRRLY-12603, *A. aceti* MCC 2109	*S. cerevisiae* NRRLY-12603 from Culture Collection, Peoria, USA; *A. aceti* MCC 2109 from National Chemical Laboratory, Pune	Sequential inoculation fermentation	Produced ethyl acetate and isopentyl alcohols	(Rudra et al., 2022)
Pomegranate	Autochthonous L. *plantarum* C2 and POM1; Commercial L. *plantarum* LP09	*L. plantarum* C2 and POM1 from Culture Collection of the Department of Soil, Plant and Food Sciences, University of Bari, Italy; *L. plantarum* LP09 from Sacco Srl, Milan, Italy	Sequential inoculation fermentation	Increased desired compounds (e.g., alcohols, ketones, and terpenes); Decreased non-desired aldehydes	(Di Cagno et al., 2017)
Grape	*S. cerevisiae* AWRI838; *Metschnikowia pulcherrima* AWRI3050; *Saccharomyces uvarum* AWRI2846; *Metschnikowia pulcherrima* AWRI3050	*S. cerevisiae* AWRI838, *Metschnikowia pulcherrima* AWRI3050, *Saccharomyces uvarum* AWRI2846 from the Australian Wine Research Institute (AWRI); *Metschnikowia pulcherrima* AWRI3050 from *M. pulcherrima* AWRI1149	Mono-strain or mixed-strain inoculation fermentation	*Metschnikowia pulcherrima* and *S. cerevisiae* AWRI838 showed higher concentrations of ethyl acetate, total esters, total higher alcohols, and total sulfur compounds; *Saccharomyces uvarum* increased the concentration of alcohols	(Varela, Barker, Tran, Borneman, & Curtin, 2017)
European cranberry	Not mentioned	Not mentioned	Natural fermentation	Increased acids, especially 3-methyl-butanoic acid; Increased Ketones and alcohols	(Yilmaztekin & Sislioglu, 2015)
Gilaburu fruit	*L. casei* (Chr. Hansen 431); *L. delbrueckii* subsp. (NBRC3202); *L. plantarum*-23	Obtained from the microbiology laboratory of Adana Alparslan Turkes Science and Technology University located in Turkey	Natural or mono-strain inoculation fermentation	*L. plantarum*-23 increased the contents of phenylethyl alcohol, hexyl acetate, and 3-hydroxy-β-damascone; Provided fruity and floral aroma	(Sevindik et al., 2022)
Mango juice	*W. saturnus var. mrakii* NCYC500, *S. cerevisiae* MERIT ferm	*W. saturnus var. mrakii* NCYC500 from National Collection of Yeast Cultures, Norwich, UK; *S. cerevisiae* MERIT ferm from Chr.-Han., Denmark	Sequential inoculation fermentation	Increased β-citronellol; Improved aroma complexity and balance	(Li, Chan, Yu, Curran, & Liu, 2014)
Italian Riesling grapes	*H. uvarum* YUN268, *P. fermentans* Z9Y-3, and *S. cerevisiae* (Excellence TXL)	*S. cerevisiae* (Excellence TXL) from LAMOTHE ABIET; *H. uvarum* YUN268 and *P. fermentans* Z9Y-3 from the Wine School of Northwest Agriculture and Forestry University	Simultaneous or Sequential inoculation fermentation	Produced more volatile aroma substances, glycerol content, and esters; Enhanced the aroma of lemon, cream, and almond	(Xia, Zhang, Sun, Zhang, & Zhang, 2023)
Grape	*T. delbrueckii*-214 (Accession number: MG017548) and *S. cerevisiae*-1088 (Accession number: MG017577)	Isolated from spontaneous fermentations of Narince grapes	Mono-or mixed-strain inoculation fermentation	Mixed fermentation increased alcohol and ester content; Improved the aromatic intensity and complexity of the wine	(Arslan, Celik, & Cabaroglu, 2018)
Mixed fruit juice (pineapple, winter melon, longan honey)	*L. plantarum* TISTR 1465; *L. salivarius* TISTR 1112; *Starmerella boulardii* CNCM I-745	Obtained from the Thailand Institute of Scientific and Technological Research	Mixed-strain inoculation fermentation	Increased alcohols (3-methyl-1-butanol, 1-hexanol, 2-phenylethanol), acetaldehyde, acetic acid, esters (ethyl acetate, ethyl 2-methylbutyrate, ethyl hexanoate, ethyl lactate, ethyl decanoate), 3-hydroxy-2-butanone, 2,4-di-tert-butylphenol, and linalool	(Laosee et al., 2022)
Sugarcane	*S. cereviasiae*; *S. cereviasiae* CCRC22580	*S. cereviasiae* was isolated from the liquor rice dregs; *S. cereviasiae* CCRC22580 from Bioresource Collection and Research Center (Food Industry and Development Institute, Hsinchu, Taiwan)	Mono-strain inoculation fermentation	Increased 1-methylethyl acetate, isoamyl acetate, ethyl hexanoate, and ethyl octanoate; Enhanced the sweet, fruity, and ester flavor of wines	(Tzeng, Chia, Tai, & Ou, 2010)

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Table 2 (*continued*)

Fruits	Strain	Strain source	Fermentation method	Flavor improvement	Reference
R. roxburghii, blueberry, plum	*S. cerevisiae* (ZYMAFLORE X16), *H. uvarum*	*S. cerevisiae* from LAFFORT (France); *H. uvarum* from China Industrial Strain Conservation Center	Simultaneous or sequential inoculation fermentation	Sequential inoculation positively affected the mellowness of the wine and achieved a better harmony of the overall wine flavors	(Huang et al., 2022)
Chardonnay grape juice added with fruit juices	*S. cerevisiae*	Not mentioned	Inoculation fermentation	Identified 29 major volatile compounds in wine, including 8 alcohols, 12 esters, 6 acids, and 3 miscellaneous compounds	(Patel & Shibamoto, 2003)
Kiwifruit	*L. acidophilus* 85, *L. helveticus* 76, *L. plantarum* 90	Purchased from WECAREBIO company (Jiangsu, China)	Mono-or mixed-strain inoculation fermentation	Improved the formation of total volatile compounds, especially for L. *helveticus* 76	(Wang et al., 2022)
Frozen sea buckthorn named “shengqiuhong”	*L. paracasei*; *S. cerevisiae*	*L. paracasei* from Xi’an Jushengyuan Biotechnology Co., Ltd. (Xi’an, China). *S. cerevisiae* from Angelyeast Inc.	Mixed-strain inoculation fermentation	Increased the sweetness of the sea buckthorn juice; Decreased the fruity flavor; Increased the bitterness	(Wu et al., 2022)
Noni fruits	*L. plantarum* CICC22703	Purchased from the China Center of Industrial Culture Collection	Inoculation fermentation	Increased methyl salicylate content; Increased the percentage of linalool, 1-Hexanol, octanol, 2-Heptanol, and α-Terpineol	(Cheng et al., 2021)
Kiwifruit	*L. plantarum* LG1034; *Pediococcus lactis* LG0259; *Bacillus rhamnosus* LG0262; *L. lactis* LG0827; *L. helveticus* LG4316; *L. paracasei* LG0260; *Kluyveromyces marxianus* J2853; *S. cerevisiae* J2861	Not mentioned	Mono-strain inoculation fermentation	*L. plantarum* LG1034, *Pediococcus. lactis* LG0259, *Bacillus rhamnosus* LG0262, *L. lactis* LG0827, and L. *helveticus* LG4316 increased polysaccharides, γ- aminobutyric acid, organic acids, and volatile compounds	(Cai et al., 2022)
Kiwifruit	*S. cerevisiae* (Drop Acid Yeast, DV10, SY and RW)	*S. cerevisiae* SY and RW from Angel Yeast CO., Ltd. (China). *S. cerevisiae* Drop Acid Yeast and DV10 from Yantai Diboshi CO., Ltd. (China) and Lallemand CO., Ltd. (China), respectively	Mono-strain inoculation fermentation	Increased (E, E)-2,4-heptadienal, fatty flavor, green aroma, 1-octen-3-one, and 4-methyl-2-pentanone fermented by *S. cerevisiae* RW	(Zhang, Chen, et al., 2023; Zhang, Hong, et al., 2023; Zhang, Ma, et al., 2023)
Passion fruit	*L. plantarum* CCMA 0743; *L. paracasei* LBC-81	*L. plantarum* CCMA 0743 from the Culture Collection of Agricultural Microbiology, Federal University of Lavras, Brazil; *L. paracasei* LBC-81 from Danisco, USA	Mono-or mixed-strain inoculation fermentation	Increased octanoic acid and hexyl ester in the mixed-strain fermentation juice	(Fonseca et al., 2022)
Nangao greengage (*Prunus mume*)	Non-saccharomyces yeasts (*Pichia terricola*, *H. occidentalis*, *Candida sorboxylosa*, *Issatchenkia orientalis*); *S. cerevisiae* BV818	Non-Saccharomyces yeasts were selected from spontaneous fermentation of greengage; *S. cerevisiae* BV818 were obtained from Angel Yeast Co. Ltd., Hubei, China	Mixed-strain inoculation fermentation	*Pichia terricola*, *H. occidentalis*, and *Issatchenkia orientalis* degraded citric acid and malic acid; *H. occidentalis* imparted fruity aroma to fermented greengage beverage; *Candida sorboxylosa* provided some higher terpenes with flowery and fruity aroma	(Qiu et al., 2022)
Kiwi fruit	*S. cerevisiae* EC1118 and Jiuqu	Jiuqu from Angel Yeast Co., Ltd. (Yichang, Hubei, China); *S. cerevisiae* EC1118 from Xinmiao Winery (Ya’an, Sichuan, China)	Mono-strain or mixed-strain inoculation fermentation	Mixed fermentation showed high quality of the final products; Decreased total organic acids and methanol contents; Increased lactic acid content	(Chen, Fu, et al., 2019; Chen, Lu, et al., 2019)
Natural ‘Langshan’ navel orange	*Lactiplantibacillus plantarum* (Lp), *L. fermentum* (Lf), *Lactobacillus acidophilus* (La), *Lacticaseibacillus rhamnosus* (Lr), *Lacticaseibacillus paracasei* (Lc), *Bifidobacterium longum* (Bl),	Lr, Lc and Bl were obtained from the China Center of Industrial Culture Collection (Beijing, China); Lp, Lf, and La were from the Key Laboratory for Fruits and Vegetables storage Processing and Quality Safety in Hunan	Mono-strain inoculation fermentation	Increased aroma-active compounds such as ᴅ-limonene, β-caryophyllene, terpinolene, and β-myrcene; Exhibited more desirable aroma flavors such as orange-like, green, woody, and lilac incense after fermentation by Lc	(Quan, Liu, Guo, Ye, & Zhang, 2022)
Apple	*S. cerevisiae* (Sc01, Sc02, Sc05, Sc12, Sc21, Sc24)	Obtained from the Department of Microbiology, HPAU, Palampur, India	Inoculation fermentation	Sc01 fermentation had the highest sensory property	(Kanwar & Keshani., 2016)
Noni fruit	*L. lactis*; *L. cremoris*; *Streptococcus thermophilus*; *L. plantarum*, *Levilactobacills brevis*; *L. acidophilus*, *L. fermentum*; *L. rhamnosus*	*L. rhamnosus* was obtained from Christian Hansen; Others were obtained from the China National Microbial Resource Center (Beijing, China)	Mono-strain inoculation fermentation	Decreased the unpleasant butanoic acid, especially in *L. plantarum* fermented noni fruit juice	(Zhang, Chen, et al., 2023; Zhang, Hong, et al., 2023; Zhang, Ma, et al., 2023)
Pinot Grigio grapes	*Lachancea thermotolerans*; *Metschnikowia* spp.; *Starmerella bacillaris*; *S. cerevisiae* EC 1118	Obtained from Local culture collection of the Department of Biotechnology of the University of Verona	Simultaneous or Sequential inoculation fermentation	*Metschnikowia* spp. promoted the formation of higher alcohols and esters, while reduced volatile phenols; *Starmerella bacillaris* increased glycerol, while reduced acetaldehyde and total SO_2; *Lachancea thermotolerans* increased	(Binati et al., 2020)

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Table 2 (*continued*)

Fruits	Strain	Strain source	Fermentation method	Flavor improvement	Reference
				lactic acid and reduced ethanol content	
Ripe bayberry fruit	*L. plantarum* CGMCC 18099; *Streptococcus thermophilus* CGMCC 18045; *L. acidophilus* CGMCC 18095; *L. bulgaricus* JYLB-19; *L. casei* CGMCC 18096; *L. helveticus* CGMCC 11159	Purchased from Zhongke-Jiayi Biological Engineering Co., Ltd. (Weifang, China)	Inoculation fermentation	Increased the concentrations of characteristic aroma volatiles, such as 2-hexenal, 1-hexanol, and (Z)-3-nonen-1-ol	(Chen et al., 2022)

S. bayanus, Saccharomyces bayanus; *W. saturnus* var. *mrakii, Williopsis saturnus* var. *mrakii*; *W. saturnus* ssp. *Saturnu, Williopsis saturnus* ssp. *Saturnu*; *S. cerevisiae, Saccharomyces cerevisiae*; *H. uvarum, Hanseniaspora uvarum*; *P. fermentans, Pichia fermentans*; *T. delbrueckii, Torulaspora delbrueckii*; *L. salivarius, Lactobacillus salivarius*; *L. delbrueckii* subsp., *Lactobacillus delbrueckii* subsp.; *H. occidentalis, Hanseniaspora occidentalis*; *L. lactis, Lactobacillus lactis*; *L. fermentum, Limosilactobacillus fermentum.*

benefits to the fruits (Table 3). The diversity in fermentation substrates and strains leads to variations in the types and amounts of these active substances. Generally, fermentation of fruits by *lactobacilli* mainly produces lactic acid, meanwhile, increases the contents of antioxidants (e.g., polyphenols), vitamins (e.g., vitamin C and vitamin K), extracellular polysaccharides, and minerals (e.g., potassium, calcium, magnesium, and iron). A study by Sevindik et al. (2022) showed that natural and inoculated fermentation of gilaburu fruits by three *lactobacilli* of *L. plantarum*, *Lactobacillus delbureckii*, and *L. casei* significantly increased polyphenol contents (e.g., chlorogenic and cryptochlorogenic acids) and minerals-potassium, especially in *L. plantarum* fermented production. Fermenting fresh lychee juice with *L. casei* for 18 h increased extracellular polysaccharide contents to 7.07 g/L, which improved the viscosity of fermented lychee juice (Zheng et al., 2014). In addition, fermentation of fruits by *lactobacilli* could change the composition and content of amino acids and fatty acids. Feng et al. (2022) showed that the levels of γ-aminobutyric acid, L-isoleucine, N-acetylornithine, and taurine in fermented elderberry juice with *L. bulgaricus* BNCC336436 and *Streptococcus thermophilus* ABT-T were significantly increased, while the relative contents of L-asparagine, L-arginine, L-aspartic acid, L-arogenate, and 10-hydroxystearic acid were significantly decreased. In addition, the contents of fatty acids including eicosapentaenoic acid, γ-linolenic acid, and sphingomyelin increased significantly.

S. cerevisiae and non-*saccharomyces* are the key microorganisms in the production of fruit wine. Polyphenols and polysaccharides are the main functional active ingredients in fruit wines, which imparts the fruit wine with excellent antioxidant, anti-inflammatory, and anti-bacterial activities. For example, Liu et al. (2021) isolated polysaccharides with molecular weights greater than 1000 kDa from beef heart plum wine fermented by *Saccharomyces cerevisiae* LalvinEC1118, which possessed great DPPH radical scavenging and α-glucosidase inhibitory activities. Lee et al. (2013) found that total polyphenols and anthocyanin contents in yeast-fermented apple pine wine and apple vanilla wine were higher, which had great antioxidant activities.

Fruit vinegar fermentation inoculated with *Acetobacter* is the next stage of fruit wine fermentation. During this stage, notable changes in bioactive substances occur. In general, the contents of organic acids (e.g., acetic, tartaric, and malic acids) and vitamins increased significantly compared to the alcoholic fermentation stage. For example, compared with black rose fruit wine, a significant increase in organic acids and vitamin C contents was observed in fruit vinegar. The composition and concentration of polyphenols and amino acids in fruit vinegar exhibit variable changes, with increases observed in certain cases and decreases in others. These alterations are contingent upon factors such as the fermenting substrates used, the specific strains involved, and the fermentation conditions applied. For example, the total polyphenol content of black rose fruit vinegar did not change compared with that of black rose fruit wine, while the content of anthocyanins and total flavonoids decreased significantly. Proline and histidine are the main amino acids in Goji fruit wine. During the fermentation of fruit vinegar, histidine increased significantly, while proline and alanine content decreased significantly (Xia et al., 2022). Altogether, fermentation of fruits could produce various active ingredients superior to those of fruit and vegetable raw materials, such as enzymes, organic acids, peptides, oligosaccharides, vitamins, flavonoids, polyphenols, amino acids, natural antibiotics, minerals, polysaccharides, as well as antioxidant components such as γ-aminobutyric acid (GABA), superoxide dismutase (SOD), catalase, etc., to increase its commercial value.

4.5. *Maintenance of health*

The development of probiotic fermented fruit products not only increases the economic value of fruits, but also organically combines probiotics and their active metabolites including polyphenols, polysaccharides, and dietary fibers. Thus, fermented fruit products exhibit outstanding health-enhancing effects including the promotion of intestinal health, the improvement of oxidative stress and inflammation, and the enhancement of immunity response (Doriya, Kumar, & Thorat, 2022). Furthermore, fermented fruit products have been used to relieve several diseases such as diabetes, cardiovascular diseases, nervous system diseases, liver damage, respiratory disease, and cancers. For example, fermented papaya has been considered a good antioxidant and an excellent nutritional aid for the intervention of Alzheimer's disease, allergic reactions, cancer, and anemia (Leitao, Ribeiro, Garcia, Barreiros, & Correia, 2022). The main reasons for the ability of fermented fruits to alleviate a wide range of diseases include antioxidant, anti-inflammatory, and immunomodulatory activities. Isas et al. (2023) showed that fermented pomegranate juice could ameliorate hyperglycemia, hyperlipidemia, fat deposition, and hepatic tissue damage in high-fat diet-induced obese C57BL/6 mice through its antioxidant activity. Kim et al. (2021) demonstrated that fermented plums of *L. plantarum* and *L. casei* were effective in reducing the risk of cancer via inhibiting oxidative stress and the expressions of pro-inflammatory factors including TNF-α, IL-1β, IL-6, IL-12, and IL-17 in DSS-induced colitis mice.

As the "second brain" of the organism, intestinal microbiota is intricately linked to a variety of chronic metabolic diseases, such as obesity, diabetes, cardiovascular, and cerebrovascular diseases. Fermented fruit products also could improve intestinal microbiota via increasing the abundance of beneficial bacteria and inhibiting the growth of harmful bacteria. A study has indicated that administration with fermented fruit increased the abundance of beneficial bacteria including *Bacteroides*, *Roseburia*, *Butyrivibrio*, *Lactobacillus*, and *Akkermansia*, thus, relieving obesity and hyperlipidemia (Yan, Wang, Weng, & Wu, 2020). While improving the structure of intestinal microbiota, the intestinal micro-environment will be also improved via increasing the levels of short-chain fatty acid and enhancing intestinal immunity (Valero-Cases, Cerda-Bernad, Pastor, & Frutos, 2020). Therefore, fermented fruits are good prebiotics for relieving kinds of diseases.

Although fermented fruits have great benefits, there are still some issues that need to be solved, including 1) The strains that can be used for fermentation is still lacking; 2) The stability of fermented fruit is

Table 3
Effects of fermentation on the active ingredients and functional activities of fruits.

Fruits	Strain	Strain source	Fermentation method	Activities	Reference
Prunus mume juice	*L. plantarum* KCTC 33131; *L. casei* KCTC 13086	Obtained from Korea Collection for Type Cultures (Jeongeup, Korea)	Mixed-strain inoculation fermentation	Alleviated the symptoms of colitis caused by DSS; Inhibited apoptosis of intestinal epithelial cells in DSS-induced colitis mice	(Kim et al., 2021)
Elderberry juice	*L. bulgaricus* BNCC336436; *Streptococcus thermophilus* ABT-T	Obtained from Food Biotechnology Laboratory at Ningbo University, China	Mixed-strain inoculation fermentation	Increased total phenolic, total amino acids, and derivatives; Decreased sucrose, l-fucose, l-malic acid, tartaric acid, and citric acid	(Feng et al., 2022)
Collagen peptide jackfruit juice	Lactic acid bacteria powder (*L. acidophilus*, *L. plantarum*, *Pediococcus pentosaceus*, *L. casei*)	Obtained from Zhongke Jiayi Co. Ltd. (Qingzhou, China)	Mixed-strain inoculated fermentation	Increased anti-oxidant capacity and lactic acid content; Promoted immune organ indexes; Alleviated the injuries of colon tissue; Stimulated cytokines and immunoglobulins; Upregulated TNF-α, IL-4, IFN-γ, IL-2, IL-10, T-bet, Foxp3, ROR-γ, and GATA3 expression; Improved gut microbiota composition and SCFAs concentration	(Ma et al., 2021)
Tremella and blueberry	*L. acidophilus*, *L. rhamnosus*, *L. casei*, *L. plantarum*, *Bifidobacterium longum*, *Bifidobacterium. lactis*, *Bifidobacterium. breve*, *Streptococcus thermophilus*	Obtained from Taiwan sub-core Biotechnology (Taiwan, China)	Mixed-strain inoculated fermentation	Decreased body weight and fat losses; Improved Proteobacteria/Bacteroidetes ratio; Increased *Allobaculum*, *Blautia*, *Parabacteroides*, and *Prevotella*; Increased short-chain fatty acids	(Sheng et al., 2021)
Blueberry	Self-made starters (*L. plantarum*, *L. acidophilus*, *L. paracasei*, *L. rhamnosus*, *L. acidipiscis*, *S. cerevisiae*); Commercial starters (*Bacillus coagulans*, *L. plantarum*, *S. cerevisiae*)	Commercial starters were from the Zhejiang Quanzhi Biotechnology Co., Ltd. (Hangzhou, China)	Natural fermentation; Inoculation fermentation of self-made starters and commercial starters	Inoculation fermentation is better than natural fermentation; Increased antioxidant potentials; Increased α-glucosidase and α-amylase inhibitory activities; Promoted the glucose consumption of HepG2 cells	(Zhong et al., 2021)
Loquat juice	*L. plantarum* LZ 22, *L. acidophilus* CICC®20709	*L. plantarum* LZ 22 was isolated from the highland barley wine koji in Tibet, China; *L. acidophilus* CICC®20709 was from the China Center of Industrial Culture Collection	Mono-strain inoculation fermentation	Enhanced antioxidant activity; Increased total flavonoid; Differentially regulated metabolites mainly in lipids and lipid-like molecules, organic acids and derivatives, amino acids, peptides, and analogs	(Meng et al., 2022)
Sea buckthorn	*L. plantarum* RM1 (MF817708)	Isolated from the Department of Food Technology, City of Scientific Research, (Rayeb milk)	Inoculation fermentation	Enhanced the functional phenolic and flavonoid contents, antioxidant, and antimicrobial activities; Increased ACE inhibitory and anticancer potentials	(El-Sohaimy et al., 2022)
Acerola and guava fruit by-product	*L. plantarum* 53, *L. paracasei* 106, *L. fermentum* 56, *L. casei* L-26	Not mentioned	Mixed-strain inoculation fermentation	Increased the contents of total flavonoids and total phenolics; Increased antioxidant activity	(de Oliveira et al., 2020)
Mixed fruit juice (pineapple, winter melon, longan honey)	*L. plantarum* TISTR 1465; *L. salivarius* TISTR 1112; *Saccharomyces boulardii* CNCM I-745	Obtained from the Thailand Institute of Scientific and Technological Research	Mono-or mixed-strain inoculation fermentation	Exhibited antioxidant activity, especially the mixed fermentation	(Laosee et al., 2022)
Prickly pear fruits	Not mentioned	Not mentioned	Not mentioned	Increased total phenolic compounds and antioxidant content	(Ben Hammouda, Castro, Duran-Guerrero, Attia, & Azabou, 2023)
Kuqa apple	*L. plantarum*, *L. reuteri*, *L. rhamnosus* and *Pediococcus pentosaceus*	Obtained from China Microbial Culture Preservation Center (Beijing, China)	Mono-strain inoculation fermentation	*Pediococcus. pentosaceus* and *L. plantarum* are the most capable for fermenting Kuqa apple juice; *L. plantarum* increased SOD activity and DPPH radical scavenging activity	(Bai, Maimaitiyiming, & Wang, 2021)
Fresh Fuji apples	*L. plantarum* CICC21809	Obtained from the China Center of Industrial Culture Collection (CICC, Beijing, China).	Inoculation fermentation	Decreased pH; Increased total phenolic and tannic contents; Upregulated L-isoleucine, L-leucine, L-valine, 4-Guanidinobutyric acid, and Phenyllactate; Reduced diarrhea in mice through regulating gut microbiota, improving intestinal morphology, and increasing the expressions of AQP 1, 8, and TJ proteins	(Guo et al., 2022)
Lemon	*Issatchenkia terricola* WJL-G4	Isolated from the fresh fruits of red raspberry	Mono-strain inoculation fermentation	Reduced citric acid; Increased total phenolic and flavonoid contents; Increased antioxidant activities	(Liu, Wei, et al., 2021; Liu, Yuan, et al., 2021)
Grape	*Oenococcus oeni* UNQOe 73.2; *L. plantarum* UNQLp 11	Isolated from Patagonian Pinot Noir wines (vintages 2008 and 2012)	Mono-strain inoculation fermentation	Both strains increased the concentration of procyanidin and diminished the concentration of phenolic substances	(Brizuela et al., 2021)

(*continued on next page*)

Table 3 (*continued*)

Fruits	Strain	Strain source	Fermentation method	Activities	Reference
Cerasus humilis fruits	*L. plantarum*, *S. cerevisiae*	Not mentioned	Not mentioned	Increased flavonoid, phenolic, procyanidin, organic, and free amino acid; Decreased total sugar contents; Ameliorated hyperlipidemia and cholesterol over-accumulation; Relieved oxidative stress; Reversed fat deposition in high-fat diet rat liver; Increased the abundance of *Prevotella* and *norank_f_Muribaculaceae*	(Wang et al., 2023)
Fuji apples	*S. cerevisiae* CICC1750; *A. pasteurianus* CICC20056	Obtained from China microbial culture preservation Center	Inoculation fermentation	Reduced the release of inflammatory cytokines induced by mononuclear leukocyte infections; Increased monocyte phagocytosis	(Song et al., 2019)
Mulberry	*Levilactobacillus brevis* F064A	Isolated from Thai fermented sausage	Inoculation fermentation	Enhanced the growth of probiotics; Increased γ- aminobutyric acid content; Improved antioxidant activities; Exhibited lipid peroxidation inhibitory activity	(Kanklai et al., 2021)
Blueberries	*L. plantarum* J26	Isolated from traditional dairy products	Inoculation fermentation	Enhanced the scavenging abilities of DPPH, superoxide anion radical, and hydroxyl radical; Alleviated oxidative damage in the model of Caco-2 cells; Increased the inhibitory effect of α-glucosidase and α-amylase	(Zhang et al., 2021)
Five varieties of mango (*Baganpalli*, *Langra*, *Dashehari*, *Alphonso*, and *Totapuri*)	*S. cerevisiae* MTCC 178; Isolated yeast	*S. cerevisiae* MTCC 178 was from Microbial Type Culture Collection (MTCC), Institute of Microbial Technology, Chandigarh (India); Isolated yeast was from Department of Plant Pathology, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi	Mixed-strain inoculation fermentation	Produced gallic acid, galloyl-A-type, proanthocyanidins, 2,2,6-trimethyl-6-vinyltetrahydropyran, β-pinene, and caffeoylquinic acid; Given potential antioxidant, anticancer, anti-inflammatory, and antibacterial properties.	(Patel, Tripathi, Adhikari, & Srivastava, 2021)
Grape	*Oenococcus oeni* MS9 and MS46	Isolated from wine collected from a cellar from Cafayate, Salta, Argentina	Mono-strain inoculation fermentation	Produced lactic acid to reduce pH; Increased total phenolic compounds with strain MS9 but not MS46; Increased antioxidant activity	(del Valle et al., 2022)
Hovenia dulcis	*S. cerevisiae*; *A. aceti*	Not mentioned	Inoculation fermentation	Increased DPPH and ABTS free radicals scavenging; Reduced power, hydrogen peroxide scavenging, and β-carotene bleaching activities; Reduced serum alcohol and acetaldehyde levels in SD rats administrated with 40% alcohol	(Park, Cho, Kim, Min, & Seo, 2023)
Fruit beverage prepared by kiwis, guavas, papayas, pineapples, and grapes	*S. cerevisiae* BCRC 21447; *L. acidophilus* BCRC 10695; *Pediococcus dextrinicus* BCRC 12842; *L. plantarum* BCRC 10069; *A. pasteurianus* BCRC 14145	Purchased from the Bioresource Collection and Research Center (BCRC; Hsinchu, Taiwan)	Mixed-strain inoculation fermentation	Reduced calorie intake; Enhanced phagocytosis and T cell proliferation; Enhanced proinflammatory cytokines production; Decreased the production of pro-inflammatory cytokines in OVA-immunized mice	(Sy, Hsu, Limaye, & Liu, 2020)
Gilaburu (*Viburnum opulus*)	*L. plantarum*; *L. delbureckii*; *L. caseii*	Obtained from microbiology laboratory of Adana Alparslan Turkes Science and Technology University in Turkey	Natural or inoculation fermentation	Increased phenolics and volatiles via inoculation fermentation	(Sevindik et al., 2022)

L. fermentum, *Lactobacillus fermentum*; *L. acidipiscis*, *Lactobacillus acidipiscis*; *L. salivarius*, *Lactobacillus salivarius*; *L. reuteri*, *Lactobacillus reuteri*; *A. niger*, *Acetobacter niger*; *L. delbureckii*; *Lactobacillus delbureckii*.

difficult to control, especially during long-term storage and transportation; 3) The quality of fermented fruit varies greatly; 4) The quality of products fermented by mono-strain fermentation is poor; 5) The synergistic effect of multiple strains and the control of fermentation process are challenges.

5. Prospects

Microbial fermentation has emerged as a prominent focus within the interdisciplinary fields of medicine and nutrition. With a growing emphasis on health, fermented fruit products have become an important part of the functional food market. Microbial fermentation can not only reduce the spoilage of fruits and improve their nutritional value, but also realize the high-value utilization of fruit processing by-products such as peel, pomace, and kernel. By summarizing the common strains applicable to fruit fermentation, common methods for fruit fermentation, and the effects of fermentation on fruit quality such as shelf-life, flavor, and functional activity, this review aims to provide a diverse theoretical basis for food innovation. Although fruit fermentation can organically combine the nutrients of fruit, probiotics, and their active metabolites-prebiotics (polyphenols, polysaccharides, and dietary fibers), the development of fruit fermentation products is still in the primary stage. There are the following points need to be studied: 1) to screen excellent microbial strains giving full play to the fruit and microbial health effects; 2) to improve fermentation technology; 3) to establish relevant industry standards proving the safety of fermented fruit products; 4) to develop fermented fruits with rich and diverse flavors meeting the different needs of people; 5) to strengthen the functionality of fermented fruit products meeting the needs of special populations.

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CRediT authorship contribution statement

Xinyu Yuan: Writing – original draft, Investigation, Data curation. **Tao Wang:** Writing – review & editing, Methodology. **Liping Sun:** Writing – review & editing, Investigation. **Zhu Qiao:** Writing – review & editing, Investigation. **Hongyu Pan:** Investigation. **Yujie Zhong:** Writing – review & editing, Project administration, Investigation. **Yongliang Zhuang:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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