Chapter 14
The Beneficial Impact of Microbes in Food Production, Health, and Sustainability

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Abstract Beneficial bacteria have a substantial impact on human health and environmental sustainability. Microbes are extremely important in a variety of food applications. They are crucial to the production of various food items. Since the beginning, multiple bacteria and fungi have been used to make multiple fermented food products and enzymes. Bread, dairy products, alcohol and drinks, enzymes, organic acids, food colours, etc., are prepared using yeast, bacteria, and fungi. These microbes are included to add appealing colour, taste, flavour, and texture and improve the product's marketability. The present chapter will focus on the use of bacteria and yeast in food processing, the production of terpenoids, lipopeptides, and polyphenols, improvement of packaging materials' effectiveness and quality through the application of nanotechnology to ensure food safety.

Keywords LPS · Bio-preservatives · Terpenoids · Sustainable

14.1 Introduction

Food processing is a branch of the manufacturing business that converts raw animal, plant, and marine ingredients into intermediate or polished, safer-to-eat food products. The objectives of food processing may include:

1. increasing the amount of time that food is wholesome,
2. giving nutrients needed for the body,

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3. offering diversity and ease in diet,
4. addition of value.

The definition of food processing is broad, and any unit operation that takes place from the time that raw materials are harvested until they are turned into food items, packaged, and delivered for retail sale may be included (Park et al., 2014). In general, these might be divided into primary and secondary processing. Primary processing, often known as post-harvest or post-slaughter processing, is food preparation for consumption or incorporation into other food products. Secondary processing transforms the prime processed food or component into new food items. It guarantees that food can be utilized for various things (Heldman & Hartel, 1998).

Although microorganisms are essential to sustaining life on the planet, we know very little about the vast microbial species found in different habitats like soils (Goel et al., 2018). Any civilization's ability to endure depends on its capacity for sustainability. When the system is socially supportive, commercially competitive, and environmentally sound, agriculture may be considered sustainable. The dynamics of growth, metabolic activity, and survival of microorganisms in food are influenced by their capacity to colonize the food matrix and develop into a spatial heterogeneity as well as by in situ cell-to-cell ecological interactions that frequently occur in a solid phase. These dynamics also involve stress responses in response to modifications in the physical and chemical conditions in the food microenvironment (Holzapfel, 2002).

Microbes are important because they are the principal dynamic factors in farming systems. Agriculturally important microorganisms control interactions between plants and other pathogenic microflora and the efficiency with which nutrients are available to agricultural plants and soil biodiversity (Singh et al., 2016). Microorganisms contribute completely to the food sector by aiding in the fermentation process that preserves food and dairy products (Gondal et al., 2021). Microorganisms are utilized in fermentation to extend food's shelf life. Since lactic acid bacteria have unique metabolic properties, they are used in many fermentation and preservation processes (Caplice & Fitzgerald, 1999). Apart from extending the shelf life of food and guaranteeing its microbiological safety, fermentation can also improve the digestibility of some foods, such as cassava, by lowering the substrate's toxicity. Lactic acid bacteria are engaged in various fermentation processes in milk, meats, cereals, and vegetables (Rakhmanova et al., 2018). Microorganisms carry out natural fermentation processes. For thousands of years, bread, vinegar, beer, yoghurt, cheese, and wine have been made using yeasts, moulds, bacteria, fruits and vegetables, and fermented fish (Fig. 14.1). One of the earliest techniques for preserving and transforming food is fermentation. This biological procedure keeps food while enhancing its nutritive and olfactory qualities. The starter culture bacteria produce lactic acid to stop the growth of unfavourable microorganisms. Food fermentation products show high economic value and have a vital role in enhancing human health. LAB have had a role in the rise of fermented foods globally, especially those that include probiotics or other bacteria that are good for your health (Soomro et al., 2002).

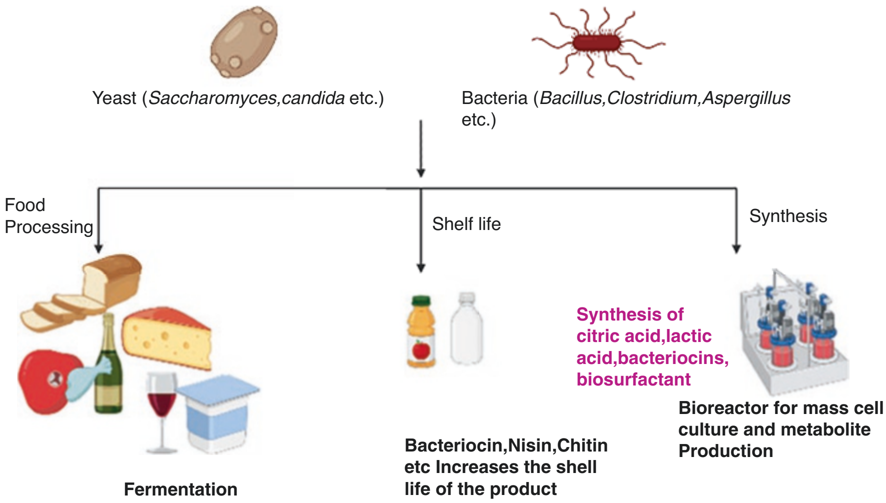

Fig. 14.1 Role of Microbes (Yeast and Bacteria) in the Food Industry

Lactococcus, Leuconostoc, Lactobacillus, and *Pediococcus* are some of the genera involved in fermentation. These bacteria create organic acids, fatty acids, and hydrogen peroxide, among other metabolic products, that have antibacterial properties. LAB produces Class III bacteriocins that hinder the growth of the pathogens involved in food spoilage. According to studies, some lactobacilli delay mycelia's development on the cheese's surface and lower the fungal population in both contaminated cheese and milk. The characteristics of *Lactobacillus plantarum* are known in biotechnology (enzyme systems, vitamins, bacteriocins, antioxidants, antimicrobial activities) and safety and quality aspects in the conventional food system (Zdolec et al., 2018). Various fermented foods are made from animal and plant sources using numerous food-grade bacteria. In addition to having a far longer shelf life than the raw materials from which they are made, foods like matured cheeses, sauerkraut, pickles, and sausages also have scent and flavour characteristics provided by the fermentation-performing organisms. Dairy products that have been fermented are becoming increasingly popular as quick, wholesome, stable, all-natural, and healthy meals. LAB is widely used to produce cultured butter, yoghurt, cheese, and sour cream. Other bacteria, known as secondary microflora, are sometimes introduced to fermented dairy products to produce carbon dioxide, affecting the flavour and changing the finished product's texture (Doyle & Meng, 2006).

Most microbial enzymes used in food processing are sold as enzyme preparations, including the needed enzyme activity, various metabolites of the manufacturing strain, and other ingredients like stabilizers and preservatives. When assessing the safety of an enzyme, the manufacturing strain's safety, specifically its toxigenic potential, continues to be the major factor to be taken into account. Fungi, known as *Aspergillus* spp., can be found in many environments, including almost all soils. These are extremely effective extracellular enzyme makers. Cellulases, pectinases, amylases, etc. that break down complex polysaccharides are produced using them commercially (Mojsov, 2016). Through the production of vitamins, and vital, proteins, improved protein and fibre digestibility, and the degradation of antinutritional components, fermentation increases food's nutritional content. It also offers a source of calories. By lowering harmful substances like aflatoxins and cyanogens and producing antimicrobial substances like lactic acid, bacteriocins, hydrogen peroxide, carbon dioxide, and ethanol that aid in suppressing or eliminating foodborne pathogens, fermentation procedures also improve food safety (Giraffa, 2004).

14.2 Factors Affecting Microbial Growth in Food

The main elements that affect microbial development in food can be summed up as follows:

1. Extrinsic factors are connected to the conditions in which the food is kept,
2. Intrinsic factors, which are elements associated with itself,
3. Processing processes,
4. Implicit factors,
5. Aspects relating to the microorganisms themselves, interactions between variables can also have a multifaceted impact on the proliferation of microorganisms in meals.

Typically, pH inhibits development in food by interacting with other factors. Pathogens and other organisms can grow more slowly when certain conditions, like pH, salt, temperature, redox potential, and preservatives, are present. Microorganisms need a few basic nutrients to thrive and maintain their metabolic processes. Depending on the organism, different nutrients have different types and necessary amounts.

Metabiotic associations are fundamental "sequence synergisms," in which the development of one microorganism leads to the development of a second, which can lead to the development of a third, and so on. An exceptional illustration of extended metabiosis is raw milk. The earliest microbes to develop in raw milk are *Lactococcus lactis* and a few coliforms. They produce lactic acid, which fosters the growth of aciduric lactobacilli. When the milk's accumulated acidity prevents lactobacilli from multiplying, oxidative yeasts and moulds start to breed and oxidize the lactic acid, elevating the milk pH and promoting the development of proteolytic bacteria (Preetha & Narayanan, 2020).

14.3 Use of Bacteria and Yeast in Food Processing

The food industry's primary goal is to process and preserve the fermented food substrate. Preparing various fermented foods, particularly those that are milk-based, and their shelf life and microbiological safety are ensured by establishing the ideal conditions for fermentation. There have also been reports of the therapeutic benefits of fermented foods.

Most fermented food manufacturing processes are unfavourable to many foodborne microbes and may even be suppressive. The antimicrobial properties of fermentation inhibit pathogens that could be present and bacteria that cause food to spoil. Therefore, potentially dangerous raw materials (such as raw milk and meat) may be employed in manufacturing food with enhanced quality and increased safety using classic food fermentation procedures (Jordan et al., 2014). Fermentation enriches the product by making a variety of tastes, textures, and scents in addition to its nutritional. Lactic acid bacteria show a crucial role in dominating role in the fermentation process (Erten et al., 2014). Single-cell proteins are cited as a source of mixed proteins and are prepared from microbes such as fungi, yeast, bacteria, and algae. Microbial cells are called single-cell proteins and natural protein sources if their cells contain a sizable amount of proteins. Due to the growing population and global protein shortage, microbial biomass is used as food. Single-cell protein has become more significant due to the growing human population and the global shortage of protein-rich microbial biomass for food and feed (Nasseri et al., 2011).

Candida yeast synthesizes extracellular metabolites such as xylitol, erythritol, biosurfactants, ethanol, and exopolysaccharides (Kieliszek et al., 2017). Bacteriocin-producing strains can be added or substituted to the starter cultures to increase the quality and safety of the fermented foods. Numerous LAB bacteriocins are natural, safe, and efficient bacterial pathogens and food-rotting inhibitors. Nisin inhibits the growth of some psychotropic bacteria in cottage cheese, stops the growth of decay lactobacilli in the fermentation of wine and beer, and provides additional protection against clostridial and bacillus spores in canned foods. It also extends the shelf life of milk in warm countries (Soomro et al., 2002).

In the nutrition of cattle and aquaculture, microbial protein is an alternative source of high-quality protein that can take the place of animal protein like fishmeal. Microalgae and algae are employed as food and supplements in the food sector. The two primary processes that use yeast are Baker's yeast and alcohol fermentation, with a worldwide market value for 2019 of up to 9.2 billion euros and a yearly growth projection of 7.9%. The most popular type of mycoprotein, QuornTM, is marketed and distributed in about 15 nations worldwide. They are particularly well suited to mimic the texture and flavour of meat, which accounts for their popularity as a substitute for traditional animal-based goods. Some cyanobacteria and microalgae are the main producers of microbial oil, which can be used in place of vegetable oil in dietary supplements. The abundant fatty acids can take the place of those typically generated from rapeseed, soy, sunflower, and palm oils (Matassa et al., 2016).

Chitin is also commonly used as a preservative in the food industry. Applying the chitin solution to egg cells before inoculation provided a barrier preventing Salmonella from penetrating. Similarly, L. monocytogenes growth on slices of sausages was inhibited by chitosan films. Adding chitin powder at a rate of 0–6% (w/w) to bread prevented the development of *B. cereus* and rope formation. Chitosan and pressure applied together synergistically removed *S. aureus* and *E. coli* from the buffer and regulated microbial growth in apple extract and minced pork in chilled storage (Malinowska-Panczyk et al., 2009).

S. salivarius, Streptococcus thermophiles, and *L. bulgaricus* ferment lactose, the milk sugar, and produces lactic acid as a by-product. These bacteria are together known as Lactic Acid Bacteria, or LAB. The bacteria consume the lactose in milk and produce lactic acid as a waste product throughout the feeding process.

A solid mass known as curd is formed by the conversion of the casein by lactic acid. The fermentation of lactose sugar into lactic acid and preservation effects gives yoghurt its jelly texture and flavour. Fermentation also enhances the diet by creating a variety of tastes, textures, and scents (Sandoval-Castilla et al., 2004).

Microbes are used in the production of chocolate. Cacao tree seeds are used to make chocolate. The pods are first fermented with naturally occurring microbes, primarily *Lactobacilli* and *Acetobacter.* Because of the increase in temperature during the fermentation process, the ethanol produced by these microorganisms kills the beans and contributes to the flavour of the chocolate (Kalsoom et al., 2020) (Table 14.1).

In the food sector, microbial enzymes are crucial because they are more stable than enzymes from plants and animals. They can be produced using fermentation processes more rapidly and inexpensively, and because of their high consistency, process adjustment and optimization are simple. The food industry uses amylases extensively for baking, starch liquefaction, brewing, and as digestive aids (van der MJEC et al., 2002). They are frequently employed as flavour enhancers and antistaling agents in the baking industry to enhance the quality of bread. During baking, yeast ferments and produce amylase enzyme. When added to the dough, it enhances the bread's flavour, colour, and toasting properties by converting starch to smaller dextrins, which are then processed into the final product (Blanco et al., 2014) with the help of amylases from *B. amyloliquefaciens*, *B.stearothermophilus,* or *Bacillus licheniformis,* most starch saccharification is accomplished. The starch in the flour is changed into maltose and fermentable sugars by enzymes called glucoseamylases. The yeast fermentation process makes the dough rise. These enzymes are also employed in synthesizing glucose, which results in ethanol formation when fermented with *Saccharomyces cerevisiae* (James et al., 1996).

The ability of yeasts like S. cerevisiae to survive in GI tract and interact antagonistically with GI pathogens such as *Escherichia coli, Salmonella,* and *Shigella* has been defined and demonstrated as one of their probiotic qualities. The industrial manufacturing of alcohol and spirits uses distiller's yeasts. They are often isolated from commercial fermentations of fruit pulps and molasses made from beets or sugar cane. At a semi-industrial scale (Bovill et al., 2001). Kefir yeasts have been

Table 14.1 Microorganism and their products

Microorganism	Process	Product	References
Saccharomyces cerevisiae	Fermentation	Bread	Heitmann et al. (2018)
Aspergillus oryzae or A. soyae	Fermentation	Soy sauce	Zhao et al. (2020)
Propionibacterium shermanii	Fermentation	Cheese	Yerlikaya et al. (2020)
S. thermophilus	Fermentation	Yoghurt	Wasilewska et al. (2019)
Saccharomyces cerevisiae and *Zigosaccharomyces rouxii*	Hydrothermal, alkali, acid, or enzymatic pre-treatments	Ethanol	Liguori et al. (2015)
Aspergillus flavus and *aspergillus tamari*	Submerged fermentation	Ascorbic acid	Mussatto & Roberto, (2005)
Monascus purpureus strain	Submerged fermentation	Colouring agent	Silbir & Goksungur, (2019)
Rhizopus spp., *Trichoderma* spp.	Hydrolysis	Single-cell protein	Bekatorou et al. (2015)
Penicillium roqueforti	Fermentation	Blue-veined cheeses	Klaenhammer (1993)
L. Lactis	Fermentation	Kefir	Jay (1996)
L. Acidophilus	Fermentation	Milk	Lee and Salminen (1995)
Lb. plantarum	Fermentation	Gari'	Oyewole and Odunfa (1990)

employed to use whey lactose and produce value-added goods such as biomass, ethanol, lactic acid, etc. (Weatherholtz & Holsing, 1975).

When making sourdough, used as a starter culture to leaven bread, flour, and water are combined with yeast and lactic acid bacteria. Compared to Baker's yeast, sourdough offers significant benefits, including the formation of distinctive flavour and texture and the extension of preservation time through the in situ generation of antibacterial compounds (such as bacteriocins). Commercially, a range of yeast and bacterial blends are employed to create sourdoughs. These sourdoughs serve to condition the dough, extend shelf life, and yield distinctive sensory attributes in bread and baked goods. (Bekatorou et al., 2015). Malolactic fermentation (MLF) is a secondary fermentation in wine often performed by LAB, particularly by *Leuconostoc oenos*, and it typically takes place after alcoholic fermentation by yeast (Liu, 2002). In this metabolic process, the malolactic enzyme catalyses the conversion of L-malic acid to L-lactic acid and CO_2 without releasing intermediates. This pathway reduces acidity, making it a vital step in manufacturing wine and cider (Faria-Oliveira et al., 2015). Several stimuli are applied to yeast and LAB cells during fermentation, including high osmotic pressure, hydrostatic pressure, and high ethanol concentrations; unusual tests on the generation of beer under anaerobic conditions, limiting temperature and nutrients were conducted on uninhabited yeast isolates from cachaça fermentation vats in Brazil (Araújo, 2013).

14.4 Food Pigments

The food business has set a high priority on developing foods with attractive looks. To make the food more enticing, different colouring agents are added. Microbial pigments must endure severe pH and temperature to meet the standard criteria for the industry (Narsing Rao et al., 2017). At a variety of pH levels, several fungi colours remain stable. The earliest known usage of fungus pigment is in Monascus. Monascus produce the yellow, orange, and purple colours frequently found in Asian cuisine (Dufosse et al., 2014). Food-grade fungi-derived pigments are now readily accessible on the market, including Monascus colours, riboflavin from Ashbya and -carotene from Blakeslea trispora (Dharmaraj et al., 2009). A wide variety of pigments, including melanin, violacein, carotenoids, pyocyanin, actinorhodin, prodigiosin, and zeaxanthin, are also produced by bacteria.

14.5 The Sustainable Production of Terpenoids, Lipopeptides, and Polyphenols

14.5.1 Terpenoids

Since microorganisms provide an efficient, ecologically acceptable way to transform low-cost raw materials such as sucrose, glucose, and biomass-derived materials into high-value compounds and fuels, manipulating microbial metabolism has significant benefits (Kampranis & Makris, 2012). One powerful class of secondary metabolites, isoprenoids, and terpenoids contribute more than 50,000 chemicals to the variety of natural product structures. The food and cosmetic industries have shown interest in using this group's members as flavour and scent additions.

The following requirements must be met by microbial hosts to synthesize terpenoids (Fig. 14.2):

1. an enormous metabolic capacity facilitating the effective synthesis of molecules that elicit interest with strong and rapid cell development;
2. well-developed genetic tools and a well-understood metabolic activity;
3. a significant capacity to grow on inexpensive carbon sources (Wang et al., 2018).

The MEP or MVA route, IPP, and DMAPP are required to synthesize terpenoids. Two representative microbial hosts are widely used to produce a variety of terpenoids.

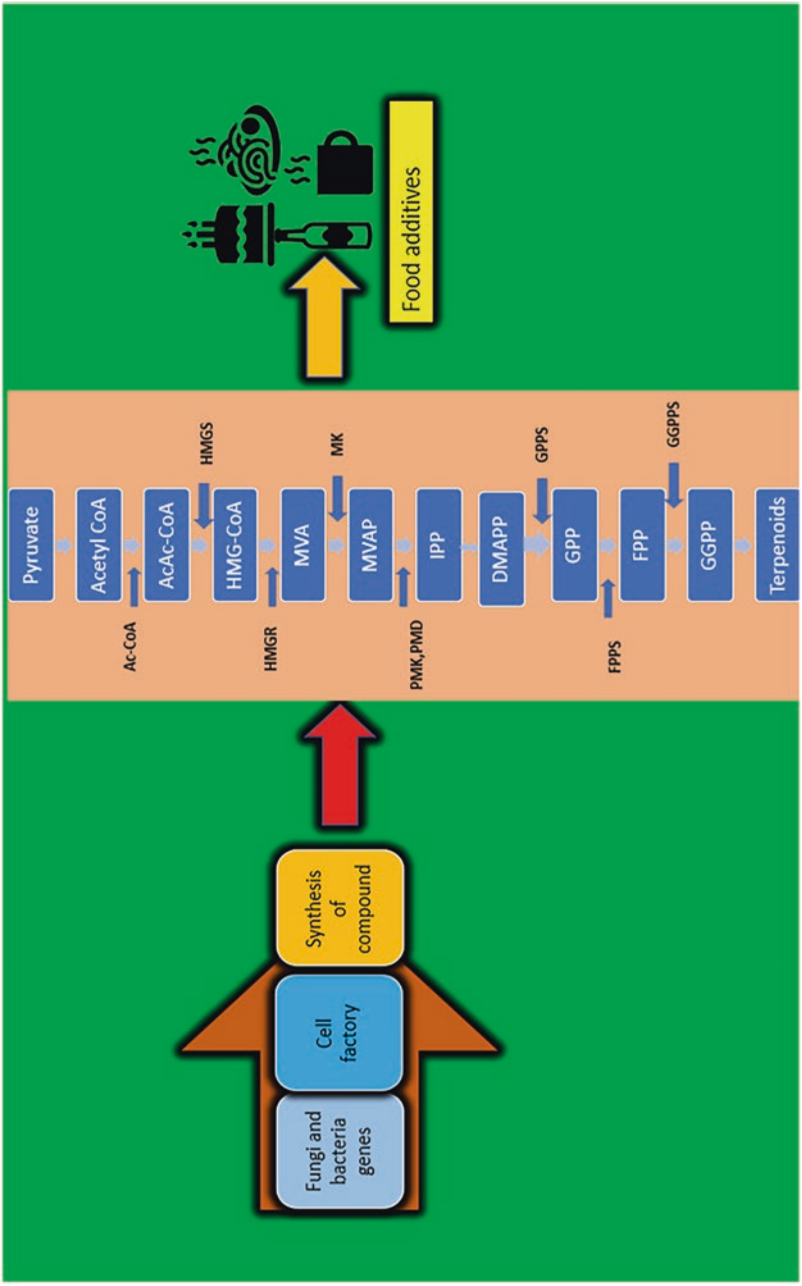

Fig. 14.2 Biosynthesis of terpenoids

1. *E. coli.*
2. *S. cerevisiae.*

The industry favours *Saccharomyces cerevisiae* over bacteria because it can handle higher osmotic pressure and a lower pH. Currently, yeast strains are being continuously developed and improved to produce large quantities of desired end products (Nevoigt, 2008). The amount of natural terpenoids produced by *E. coli* is relatively low. S. cerevisiae accumulates a lot of ergosterol, which opens up the possibility of using its MVA route to produce terpenoids. Contrary to *E. coli*, *S. cerevisiae* contains redox mechanisms that enable cytochrome P450 to change the terpenoids' skeleton. In synthesizing value-added terpenoids with complex structures, *S. cerevisiae* is superior to *E. coli* (Zhu & Jackson, 2015).

14.5.2 Lipopeptides

Surfactin has been given preference in several commercial uses. Lipopeptides' existence in fermented food products was also considered for its uses in the food industry. Additionally, their capacity to cause systemic resistance in plants and their role in bacterial cell spread that results in rhizosphere colonization may open up new avenues for their potential use as phytopharmaceutical agents. Lipopeptides are not poisonous, biodegradable, stable, environmentally favourable, or polluting biomolecules. These characteristics of the lipopeptides make them more effective biologics for use in food, medicine, and food processing (Meena & Kanwar, 2015, b).

Two categories of microbial surfactants are recognized:

1. Lipopeptides and Glycolipids—low molecular weight biosurfactants,
2. Lipoproteins and polysaccharides—high molecular weight biosurfactants.

The emulsifying ability of the low molecular weight molecule can be used in the bioremediation of hydrophobic chemicals in various environments. Several microorganisms produce lipopeptide surfactants, which have structures with different chemical and surface characteristics. The intracellular or extracellular parts of fungi, bacteria, and yeast synthesize the surfactants. The synthesis of value-added metabolites from renewable substrates is one of the industrial processes involving biotechnology products (Kumar & Ngueagni, 2021).

As each molecule of biosurfactant contains both hydrophobic and hydrophilic moieties, they are amphiphilic secondary metabolites with surface and interfacial action. Because of this, BS can lower surface tension or dissolve hydrophobic compounds in water. They are seen as "green" substitutes for chemical surfactants (Biniarz et al., 2017).

Bacillus species primarily release lipopeptides (LPs), a unique class of natural antimicrobial peptides, through NRPS pathways. LPs typically forms connection with the membrane, creating a pore that causes the microbial membrane to become unstable (Zhang et al., 2022). However, on the basis of the kind and structures of these lipopeptides, changes in the mechanism of act against different pathogenic and spoilage microbe have been identified among the described LPs. In addition to improving antibacterial activity, Bacillus spp. can better preserve orange fruit during storage by fabricating (metal particles into LPs (Zhou et al., 2021). Some microorganisms produce biosurfactants that are extensively used in the food industry. *Candida* and *Yarrowia* are among the yeasts used for the production of biosurfactants and the synthesis of emulsifiers. Due to the lack of toxicity or pathogenicity risks, these microorganisms can be used in the food sector. These yeasts include *Yarrowia lipolytica, S. cerevisiae,* and *Kluyveromyces lactis.*

The majority of food industry goods' consistency, texture, dispersion, and scent solubilization are all influenced by emulsification. An emulsifier prevents globule clustering and maintain an aerated environment to stabilize the emulsion. Studies have shown that *Candida valida, Rhodotorula graminis*, the red alga, and bacteria from the *Klebsiella* sp. and *Acinetobacter calcoaceticus* are widely used as emulsifiers. They show better-stabilizing activity than carboxymethyl cellulose and gum arabic (Campos et al., 2013) (Table 14.2).

14.5.3 Polyphenols

Secondary metabolites from plants and polyphenols are mostly present in foods made of plants, including fruits, vegetables, herbs, legumes, spices, and tea. The health advantages of polyphenol are increased by hydrolysis and change from bound to free form caused by microbial fermentation (Sarkar et al., 2022). Fruit

Table 14.2 Biosurfactant-producing microbes and their function in food processing and preservation

Type	Function	Application	References
Candida lipolytica	Emulsifier	Food fermentation	Barros et al. (2007)
Candida utilis	Emulsifier	Salad decoration	Shepherd et al. (1995)
Saccharomyces cerevisiae	Stabilize water–oil	Formation of mayonnaise, cookies, etc.	Barros et al. (2007)
Klebsiella	Emulsifier	Inhibition of the autooxidation of soybean oil.	Kawaguchi et al. (1996)
Lactobacillus	Adhesive	Coating agents for food-related utensils	Gudina et al. (2010)
Nesterenkonia	Emulsifier	Antioxidant activity and protective against *S. aureus*	Kiran et al. (2017)
Bacillus	Antimicrobial	Shows antimicrobial activity against food-spoiling bacteria	Kourmentza et al. (2021)
Bacillus subtilis (Surfactins)	Emulsifier	Maintain the texture, stability, and volume and also aid in the emulsification of fat to regulate the accumulation of fat globules	Meena and Kanwar (2015)

wine's glucosidase production by non-*Saccharomyces cerevisiae* was essential. Alcohols, esters, acids, terpenes, and other volatile compounds may be produced during the hydrolysis of glycoside-bound volatiles in fruit juice by non-*Saccharomyces cerevisiae* with glucosidase activity (Fig. 14.3). It enhanced the fruit wine's flavour and aroma (Li et al., 2022). The naringenin, flavanones, and pinocembrin, formed from the phenylpropanoids p-coumaric acid and cinnamic acid, respectively, were the first plant-derived polyphenols to be synthesized in a microbe. Alternative hosts for the microbial synthesis of polyphenols, including *Corynebacterium glutamicum*, *L. lactis,* and *Streptomyces venezuelae*, have been effectively introduced (Milke et al., 2018) (Table 14.3).

Ascomycetes, deuteromycetes, and basidiomycetes all include laccases, which have great potential for application in the food industry as processing aids.

The usage of laccase includes bioremediation, beverage stability, uses in the banking sector, and a contribution to the enhancement of overall food quality. Despite turbidity, laccase treatment and active filtering significantly boosted colour stability, according to research. Juices treated with laccase have been reported to have significantly less phenolic content and more stable colour. Additionally, it has been discovered that laccase treatment is superior to standard colour and flavour stability methods, such as adding sulphites and ascorbic acid (Brijwani et al., 2010).

During cassava fermentation for gari preparation, it was observed that *L. plantarum* was frequently isolated as a LAB species. Due to the production of many antimicrobial metabolites during fermentation, lactic acid fermentation extends the shelf life of fermented items. The produced compounds such as organic acids,

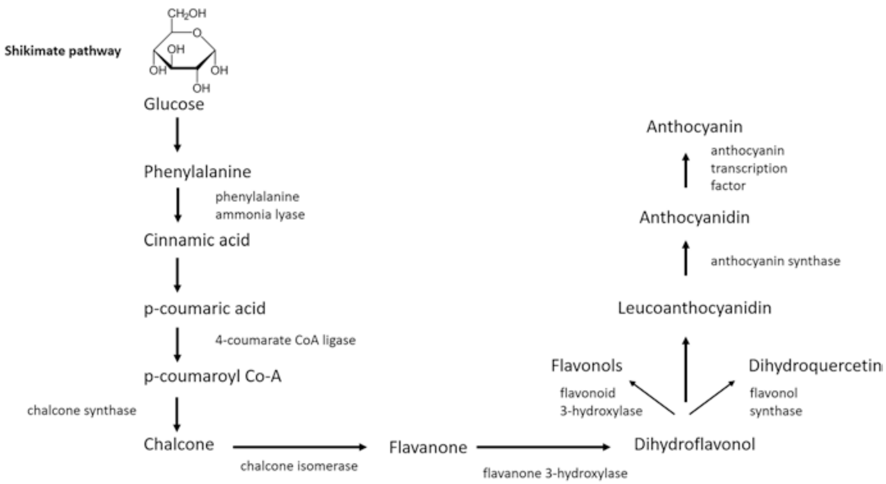

Fig. 14.3 Biosynthesis of Polyphenols

Table 14.3 Microorganisms and their polyphenol products

Product	Organism	References
Isoflavone genistein	*E. coli* and *S. cerevisiae*	Leonard and Koffas (2007)
Resveratrol	*E. coli* and *C. glutamicum*	Heo et al. (2017)
Kaempferol, quercetin lucoside	*Bacillus cereus* or *Xanthomonas campestris*	Hyung Ko et al. (2006)
Sakuranetin	*E. coli*	Kim et al. (2013)
Resveratrol	*Flavobacterium johnsoniae*	Kallscheuer et al. (2016)
Resveratrol	*S. cerevisiae*	Li et al. (2016)
Ferulic acid	*E. coli*	Kang et al. (2014)
Kaempferol	*S. cerevisiae*	Duan et al. (2017)

generate an acidic environment that is adverse to the growth of harmful and unwanted microbes (Adesulu-Dahunsi et al., 2020). Other antimicrobial bioactive compounds that LAB can produce include hydrogen peroxide, ethanol diacetyl, and bacteriocins. By reducing the antinutrient content of FFB through lactic acid fermentation, the bioavailability of vital dietary minerals in food items is enhanced (O'Sullivan et al., 2010).

The synergistic interaction of LAB and yeast carries out the traditional fermentation of cereals. According to research, LAB's acidifying environment favours yeast growth in fermented items. Yeast, which can supply growth factors, including vitamins and soluble nitrogen molecules, can encourage the growth of LAB. During the fermentation process of cereal for the production of ogi, the association of yeast species (*S. cerevisiae, R. graminis,* etc.) and LAB species (*L. fermentum, L. plantarum,* etc.) have been reported (Teniola et al., 2022). Incorporating phenolic substances such as curcumin, quercetin, and catechin into the foil matrix is one technique to enhance food quality. The use of phenolic compounds in packaging foil has been demonstrated to increase product shelf life and have high antioxidant effects, avoiding oxidation of lipid in fresh ground pork (Gutiérrez-del-Río et al., 2021).

14.6 Improvement of Packaging and Quality Through Nanotechnology to Ensure Food Safety

Food packaging's principal objective is to shield the product from its environment. Maintaining the food's quality throughout the product's shelf life is another goal. Additionally, packaging needs to consider legal, commercial, and communication requirement. Product qualities, attributes, and storage and distribution conditions of the individual packaging all affect how long a product will last.

If properly utilized, the growing field of nanotechnology could completely transform the global food processing and packaging industries. From processing and manufacture to handling and storage, till the products reach consumers, food packaging is crucial for protecting the safety and quality of foodstuffs. Food quality degrades because many fresh fruits and vegetables are susceptible to abiotic factors and ethylene (Mustafa & Andreescu, 2020). Recent research has indicated that covering food surfaces with natural or biopolymers can help preserve food. Various beverages, including fruit juices, tea, and coffee, can be clarified, maintained, and encapsulated using chitosan-based matrices, according to a new study (Sridhar et al., 2021). To increase the shelf life of various fruits and vegetables, bionanoencapsulated quercetin (biodegradable poly-D,L-lactide) should be employed, as it has improved the shelf life of tomatoes. The most widely used products made using nanotechnology include Nanogreen Tea, Neosino capsules, Canola Active Oil, Aquanova, and Nutralease (Bratovcic, 2020).

The use of nanoparticles in food has several objectives:

1. using nanoencapsulation to safeguard and enhance the stability of nutritional components, minerals, or nutraceuticals (Fathi et al., 2012).
2. for food product fortification, coating surfaces with protective nanomaterials to provide protective functions (Kiran et al., 2017).
3. fillers to improve the mechanical properties of packaging (Majeed et al., 2013).
4. sensing materials to create in situ food quality and safety monitoring techniques, ideally attached to or included in the packaging (Mills et al., 2012).

Nutraceuticals, viscosifying agents, gelation, nutrition delivery, vitamin fortification, gelation, and nanoencapsulation of tastes are just a few of the food processing techniques that use nanomaterials. The major reasons why food is processed are to preserve the food's integrity and lengthen its shelf life. Enzymes can be employed in a variety of food processing methods to alter food ingredients to enhance flavour, nutritional value, and health advantages, among other things (Asadi & Mousavi, 2006). Due to their assistance in dispersion in food matrices and their larger surface-to-volume ratios when compared to conventional macro-scale support materials, nanomaterials offer superior enzyme support systems. For instance, nano-silicon dioxide particles successfully hydrolysed olive oil, increasing its stability, adaptability, and reusability (Rashidi & Khosravi-Darani, 2011).

Antimicrobial packaging, also referred to as active packaging, comes into contact with the food item or the headspace inside to stop or impede any possible microbial development on food surfaces (Carbone et al., 2016). Many nanoparticles, including silver, copper, chitosan, and metal oxide nanoparticles like titanium or zinc oxide, have demonstrated antibacterial capabilities. Chitin or chitosan addition enhances the weight, toughness, fire resistance, and thermal properties of the polymer matrix (Singh et al., 2017a, b).

Numerous complex technologies have been made possible by nanotechnology and encapsulating methods (Fig. 14.4), allowing the design of devices for application in the food sector. These nanostructured devices could be very advantageous in many areas of food science (Singh et al., 2017a, b). Nanofibers can add additional functional characteristics as well as mechanical strength to preserve foods with delicate textures better. Due to its antioxidant features, green tea has been widely used

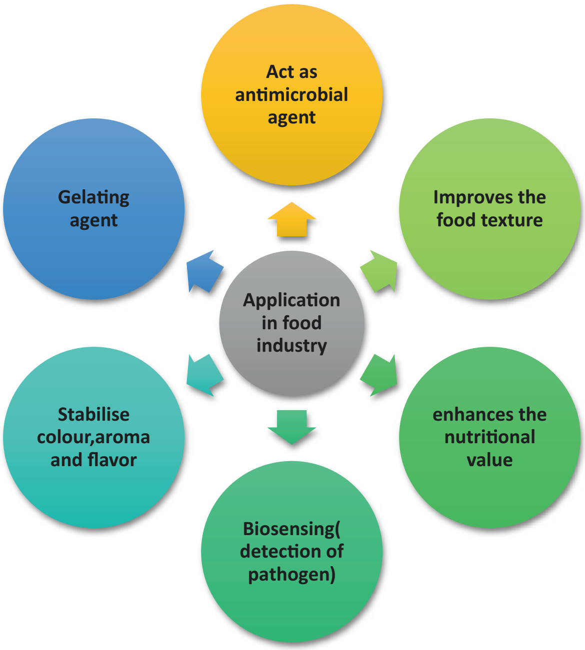

Fig. 14.4 Application of nanotechnology in the food industry

to make edible food packaging materials due to its antioxidant characteristics. The use of nanomaterial goods as food colour additives, which play a key role in the psychological attractiveness of consumer products, has just received approval. Furthermore, the nanocoatings on various edible food components might serve as a barrier to moisture and gas exchange, transmit flavours, colours, and anti-browning agents, and lengthen the shelf life of manufactured meals (Dwivedi et al., 2018).

New quercetin-starch-based films made on biodegradable chitosan-gelatin have been created. When compared to the control without flavonoid incorporation, it was found that the film containing quercetin-starch improved antioxidant activity. Biodegradable poly-(ester-urethane) film that is loaded with catechin act as an antioxidant agent and is based on a triblock copolymer of poly-(lactic acid) and poly-(caprolactone). This novel material demonstrated effective antioxidant activity, good catechin release, and suitable compost decomposition. A whey protein film synthesized using hydroethanolic extracts of the brown edible macroalgae *Fucus vesiculosus L* act as an active package that can prevent chicken breasts from oxidizing during a 25-day storage period. Under the right environmental conditions, it is possible to trigger the partial breakdown of the milk protein known as lactalbumin by a protease to self-assemble into comparable nanotubes and can be employed in food, nanotechnology, and many more (Rashidi & Khosravi-Darani, 2011).

Microorganism- or bacterial-produced polymers (such as polyhydroxybutyrate, bacterial cellulose, xanthan, curdian, and pullan) are frequently utilized in food packaging.

It is simple to manufacture lactic acid, the PLA's monomer, through the fermentation of a carbohydrate feedstock. Crops such as corn, wheat, molasses, and whey are examples of possible carbohydrate feedstock. Many different bacteria store PHB as carbon and energy reserves. This polyester may easily find commercial uses due to its biodegradability and biocompatibility (PLA and PHB may present a wide range of packaging application potential (Wesley et al., 2014).

A polysaccharide produced from chitin, chitosan is present in the exoskeletons of crustaceans, arthropods, and fungi. Chitosan is a possible nanoparticle for packaging since it is safe for the environment, non-toxic, and has great antibacterial effects. Chitosan enhances the gas and moisture barrier qualities when added to a biodegradable polymer, such as PA films. Due to their hydrophobic nature, hydrogen production, and covalent interaction between biopolymer and chitosan nanoparticles, which slows moisture diffusion, they also enhance antibacterial capabilities and impermeability (Ashfaq et al., 2022).

14.7 Conclusion

Any compound with nutritional value is considered food, and when consumed, the body uses it to produce energy and maintain life. Wine, beer, brews, champagne, and other alcoholic beverages are all produced with the help of *Saccharomyces* species. Due to their flavour and health advantages, fermented foods, probiotics, and alcoholic beverages are becoming increasingly popular today. Innovative techniques have been created as a result of technological improvement, opening up a varied series of applications for microorganisms in the food and beverage industries. Numerous routes help produce energy at the cellular level.

Furthermore, positive outcomes have been obtained in using microbes for food preservation, where they may shield the food from moisture, lipids, gases, off-tastes, and aromas. Effective microbial communities that can provide services such as nutrient use efficiency, bioremediation, food packaging quality, food fermentation, and control of phytopathogens at the farming level are well known. They offer excellent vehicle systems to deliver bioactive compounds to the target tissues. Biofilms covering fruits and vegetables are also a hot topic. Bacteria are beneficial in a variety of biological and culinary industries. For these microbial communities to be widely used in the food industry, a comprehensive understanding of the environmental conditions impacting their viability and performance is required. This intriguing technology is widely used in industrial applications, but several problems still need to be addressed and handled, including regulatory concerns and effectiveness. Understanding microbes that offer superior stability, efficacy, and cost-effectiveness must be the focus of future research.

References

Adesulu-Dahunsi, A. T., Dahunsi, S. O., & Olayanju, A. (2020). Synergistic microbial interactions between lactic acid bacteria and yeasts during production of Nigerian indigenous fermented foods and beverages. *Food control, 110*, 106963.

Araújo, T. M. (2013). *Caracterização bioquímico-molecular de cepas de Saccharomyces cerevisiae isoladas de dornas de fermentação de cachaça Para produção de cervejas [thesis]*. Universidade federal de Ouro Preto.

Asadi, G., & Mousavi, S. M. (2006). Application of nanotechnology in food packaging. In *13th world congress of Food Science & Technology* (pp. 739–739).

Ashfaq, A., Khursheed, N., Fatima, S., Anjum, Z., & Younis, K. (2022). Application of nanotechnology in food packaging: pros and cons. *Journal of Agriculture and Food Research, 7*, 100270.

Barros, F. F. C., Quadros, C. P., Marostica Junior, M. R., & Pastore, G. M. (2007). Surfactina: propriedades quımicas, tecnologicas e funcionais para aplicac¸~oes em alimentos. *Quimica Nova, 30*, 409–414.

Bekatorou, A., Plessas, S., & Mantzourani, I. (2015). Biotechnological exploitation of brewery solid wastes for recovery or production of value-added products. In R. V. Ravishankar (Ed.), *Advances in food biotechnology* (1st ed., pp. 393–414). Wiley.

Biniarz, P., Łukaszewicz, M., & Janek, T. (2017). Screening concepts, characterization and structural analysis of microbial-derived bioactive lipopeptides: a review. *Critical Reviews in Biotechnology, 37*(3), 393–410.

Blanco, C. A., Caballero, I., Barrios, R., & Rojas, A. (2014). Innovations in the brewing industry: light beer. *International Journal of Food Sciences and Nutrition, 65*, 655–660. https://doi.org/10.3109/09637486.2014.893285

Bovill, R., Bew, J., & Robinson, S. (2001). Comparison of selective media for the recovery and enumeration of probiotic yeasts from animal feed. *International Journal of Food Microbiology, 67*, 55–61.

Bratovcic, A. (2020). Nanomaterials in food processing and packaging, its toxicity and food labeling. *Acta scientific nutritional health, 4*(9), 07–13.

Brijwani, K., Rigdon, A., & Vadlani, P. V. (2010). Fungal laccases: production, function, and applications in food processing. *Enzyme research, 2010*, 149748.

Campos, J. M., Montenegro Stamford, T. L., Sarubbo, L. A., de Luna, J. M., Rufino, R. D., & Banat, I. M. (2013). Microbial biosurfactants as additives for food industries. *Biotechnology Progress, 29*(5), 1097–1108.

Caplice, E., & Fitzgerald, G. F. (1999). Food fermentations: role of microorganisms in food production and preservation. *International Journal of Food Microbiology, 50*(1–2), 131–149. https://doi.org/10.1016/S0168-1605(99)00082-3

Carbone, M., Donia, D. T., Sabbatella, G., & Antiochia, R. (2016). Silver nanoparticles in polymeric matrices for fresh food packaging. *Journal of King Saud University-Science, 28*(4), 273.

Dharmaraj, S., Ashokkumar, B., & Dhevendaran, K. (2009). Food-grade pigments from Streptomyces sp. isolated from the marine sponge Callyspongia diffusa. *Food Research International, 42*(4), 487–492.

Doyle, M. P., & Meng, J. I. A. N. G. H. O. N. G. (2006). Bacteria in food and beverage production. *Prokaryotes, 1*, 797–811.

Duan, L., Ding, W., Liu, X., Cheng, X., Cai, J., Hua, E., & Jiang, H. (2017). Biosynthesis and engineering of kaempferol in *Saccharomyces cerevisiae*. *Microbial Cell Factories, 16*(1), 165. https://doi.org/10.1186/s12934-017-0774-x

Dufosse, L., Fouillaud, M., Caro, Y., Mapari, S. A., & Sutthiwong, N. (2014). Filamentous fungi are large-scale pro.

Dwivedi, C., Pandey, I., Misra, V., Giulbudagian, M., Jungnickel, H., Laux, P., & Singh, A. V. (2018). The prospective role of nanobiotechnology in food and food packaging products. *Integrative Food Nutrition Metab, 5*.

Erten, H., Ağirman, B., Gündüz, C. P. B., Çarşanba, E., Sert, S., Bircan, S., & Tangüler, H. (2014). Importance of yeasts and lactic acid bacteria in food processing. In *Food processing: strategies for quality assessment* (pp. 351–378). Springer.

Faria-Oliveira, F., Diniz, R. H., Godoy-Santos, F., Piló, F. B., Mezadri, H., Castro, I. M., & Brandão, R. L. (2015). The role of yeast and lactic acid bacteria in the production of fermented beverages in South America. *Food production and industry*, 107–135.

Fathi, M., Mozafari, M. R., & Mohebbi, M. (2012). Nanoencapsulation of food ingredients using lipid based delivery systems. *Trends in Food Science and Technology, 23*(1), 13–27.

Giraffa, G. (2004). Studying the dynamics of microbial populations during food fermentation. *FEMS Microbiology Reviews, 28*(2), 251–260.

Goel, R., Kumar, V., Suyal, D. C., Narayan, & Soni, R. (2018). Toward the unculturable microbes for sustainable agricultural production. In *Role of rhizospheric microbes in soil* (pp. 107–123). Springer.

Gondal, A. H., Farooq, Q., Hussain, I., & Toor, M. D. (2021). Role of microbes in plant growth and food preservation. *Agrinula: Jurnal Agroteknologi Dan Perkebunan, 4*(2), 106–121.

Gudina, E. J., Teixeira, J. A., & Rodrigues, L. R. (2010). Isolation and functional characterization of a biosurfactant produced by lactobacillus paracasei. *Colloids and Surfaces. B, Biointerfaces, 76*, 298–304.

Gutiérrez-del-Río, I., López-Ibáñez, S., Magadán-Corpas, P., Fernández-Calleja, L., Pérez-Valero, Á., Tuñón-Granda, M., & Lombó, F. (2021). Terpenoids and polyphenols as natural antioxidant agents in food preservation. *Antioxidants, 10*(8), 1264.

Heitmann, M., Zannini, E., & Arendt, E. (2018). Impact of Saccharomyces cerevisiae metabolites produced during fermentation on bread quality parameters: a review. *Critical Reviews in Food Science and Nutrition, 58*(7), 1152–1164.

Heldman, D. R., & Hartel, R. W. (1998). *Principles of food processing*. Springer.

Heo, K. T., Kang, S.-Y., & Hong, Y.-S. (2017). *De novo* biosynthesis of pterostilbene in an *Escherichia coli* strain using a new resveratrol *O*-methyltransferase from *Arabidopsis*. *Microbial Cell Factories, 16*(1), 30.

Holzapfel, W. H. (2002). Appropriate starter culture technologies for small-scale fermentation in developing countries. *International Journal of Food Microbiology, 75*(3), 197–212.

Hyung Ko, J., Gyu Kim, B., & Joong-Hoon, A. (2006). Glycosylation of flavonoids with a glycosyltransferase from *Bacillus cereus*. *FEMS Microbiology Letters, 258*(2), 263–268.

James, J., Simpson, B. K., & Marshall, M. R. (1996). Application of enzymes in food processing. *Critical Reviews in Food Science and Nutrition, 36*, 437–463. https://doi.org/10.1080/10408399609527735

Jay, J. M. (1996). *Modern food microbiology* (5th ed.). Chap man and Hall.

Jordan, K., Dalmasso, M., Zentek, J., Mader, A., Bruggeman, G., Wallace, J., De Medici, D., et al. (2014). Microbes versus microbes: control of pathogens in the food chain. *Journal of the Science of Food and Agriculture, 94*(15), 3079–3089.

Kallscheuer, N., Vogt, M., Stenzel, A., Gätgens, J., Bott, M., & Marienhagen, J. (2016). Construction of a *Corynebacterium glutamicum* platform strain for the production of stilbenes and (2*S*)-flavanones. *Metabolic Engineering, 38*, 47–55.

Kalsoom, M., Rehman, F. U., Shafique, T. A. L. H. A., Junaid, S. A. N. W. A. L., Khalid, N., Adnan, M., & Ali, H. (2020). Biological importance of microbes in agriculture, food and pharmaceutical industry: a review. *Innovare Journal Life Sciences, 8*(6), 1–4.

Kampranis, S. C., & Makris, A. M. (2012). Developing a yeast cell factory for the production of terpenoids. *Computational and Structural Biotechnology Journal, 3*(4), e201210006.

Kang, S.-Y., Lee, J. K., Choi, O., Kim, C. Y., Jang, J.-H., Hwang, B. Y., & Hong, Y.-S. (2014). Biosynthesis of methylated resveratrol analogs through the construction of an artificial biosynthetic pathway in *E. coli*. *BMC Biotechnology, 14*(1), 67.

Kawaguchi, K., Satomi, K., Yokoyama, M., & Ishida, Y. (1996). Antioxidative properties of an extracellular polysaccharide produced by a bacterium Klebsiella sp. isolated from river water. *Nippon Suisan Gakkaishi, 42*, 243–251.

Kieliszek, M., Kot, A. M., Bzducha-Wróbel, A., BŁażejak, S., Gientka, I., & Kurcz, A. (2017). Biotechnological use of candida yeasts in the food industry: a review. *Fungal Biology Reviews, 31*(4), 185–198.

Kim, M.-J., Kim, B.-G., & Ahn, J.-H. (2013). Biosynthesis of bioactive *O*-methylated flavonoids in *Escherichia coli*. *Applied Microbiology and Biotechnology, 97*(16), 7195–7204.

Kiran, G. S., Priyadharsini, S., Sajayan, A., Priyadharsini, G. B., Poulose, N., & Selvin, J. (2017). Production of lipopeptide biosurfactant by a marine Nesterenkonia sp. and its application in food industry. *Frontiers in Microbiology, 8*, 1138.

Klaenhammer, T. R. (1993). Genetics of bacteriocins produced by starter culture lactic acid bacteria. *FEMS Microbiology Reviews, 12*, 39–86.

Kourmentza, K., Gromada, X., Michael, N., Degraeve, C., Vanier, G., Ravallec, R., & Jauregi, P. (2021). Antimicrobial activity of lipopeptide biosurfactants against foodborne pathogen and food spoilage microorganisms and their cytotoxicity. *Frontiers in Microbiology, 11*, 561060.

Kumar, P. S., & Ngueagni, P. T. (2021). A review on new aspects of lipopeptide biosurfactant: types, production, properties and its application in the bioremediation process. *Journal of Hazardous Materials, 407*, 124827.

Lee, Y.-K., & Salminen, S. (1995). The coming of age of probiotics. *Trends in Food Science and Technology, 6*, 241–245.

Leonard, E., & Koffas, M. A. (2007). Engineering of artificial plant cytochrome P450 enzymes for synthesis of isoflavones by *Escherichia coli*. *Applied and Environmental Microbiology, 73*(22), 7246–7251. https://doi.org/10.1128/AEM.01411-07

Li, M., Schneider, K., Kristensen, M., Borodina, I., & Nielsen, J. (2016). Engineering yeast for high-level production of stilbenoid antioxidants. *Scientific Reports, 6*, 36827.

Li, S., Bi, P., Sun, N., Gao, Z., Chen, X., & Guo, J. (2022). Characterization of different non-saccharomyces yeasts via mono-fermentation to produce polyphenol-enriched and fragrant kiwi wine. *Food Microbiology, 103*, 103867.

Liguori, R., Soccol, C., de Souza, P., Vandenberghe, L., Woiciechowski, A., & Faraco, V. (2015). Second generation ethanol production from brewers' spent grain. *Energies, 8*(4), 2575–2586.

Liu, S. Q. (2002). Malolactic fermentation in wine–beyond deacidification. *Journal of Applied Microbiology, 92*(4), 589–601.

Majeed, K., Jawaid, M., Hassan, A. A. B. A. A., Bakar, A. A., Khalil, H. A., Salema, A. A., & Inuwa, I. (2013). Potential materials for food packaging from nanoclay/natural fibres filled hybrid composites. *Materials Design, 46*, 391–410.

Malinowska-Panczyk, E., Kolodziejska, I., Murawska, D., & Wolosewicz, G. (2009). The combined effect of moderate pressure and chitosan on Escherichia coli and Staphylococcus aureus cells suspended in a buffer and on natural microflora of apple juice and minced pork. *Food Technology and Biotechnology, 47*(2), 202.

Matassa, S., Boon, N., Pikaar, I., & Verstraete, W. (2016). Microbial protein: future sustainable food supply route with low environmental footprint. *Microbial Biotechnology, 9*(5), 568–575.

Meena, K. R., & Kanwar, S. S. (2015). Lipopeptides as the antifungal and antibacterial agents: applications in food safety and therapeutics. *BioMed research international, 2015*.

Milke, L., Aschenbrenner, J., Marienhagen, J., & Kallscheuer, N. (2018). Production of plant-derived polyphenols in microorganisms: Current state and perspectives. *Applied Microbiology and Biotechnology, 102*(4), 1575–1585.

Mills, A., Lawrie, K., Bardin, J., Apedaile, A., Skinner, G. A., & O'Rourke, C. (2012). An O2 smart plastic film for packaging. *Analyst, 137*(1), 106–112.

Mojsov, K. D. (2016). Aspergillus enzymes for food industries. In *New and future developments in microbial biotechnology and bioengineering* (pp. 215–222). Elsevier.

Mussatto, S. I., & Roberto, I. C. (2005). Acid hydrolysis and fermentation of brewer's spent grain to produce xylitol. *Journal of the Science of Food and Agriculture, 85*(14), 2453–2460.

Mustafa, F., & Andreescu, S. (2020). Nanotechnology-based approaches for food sensing and packaging applications. *RSC Advances, 10*(33), 19309–19336.

Narsing Rao, M. P., Xiao, M., & Li, W. J. (2017). Fungal and bacterial pigments: secondary metabolites with wide applications. *Frontiers in microbiology, 8*, 1113.
Nasseri, A. T., Rasaul, S., Morowvat, M. H., & Ghasemi, Y. (2011). Single cell protein: production and process. *American Journal of Food Technology, 6*(2), 103–116.
Nevoigt, E. (2008). Progress in metabolic engineering of Saccharomyces cerevisiae. *Microbiology and Molecular Biology Reviews, 72*(3), 379–412.
O'Sullivan, L., Murphy, B., McLoughlin, P., Duggan, P., Lawlor, P. G., Hughes, H., & Gardiner, G. E. (2010). Prebiotics from marine macroalgae for human and animal health applications. *Marine Drugs, 8*(7), 2038–2064.
Oyewole, O. B., & Odunfa, S. A. (1990). Characterization and dismonocytogenes in cottage cheese manufactured with a lacticin tribution of lactic acid bacteria in cassava fermentation duringfufu production. *The Journal of Applied Bacteriology, 68*, 145–152.
Park, S. H., Lamsal, B. P., & Balasubramaniam, V. M. (2014). Principles of food processing. *Food processing: principles and applications, 2*, 1.
Preetha, S. S., & Narayanan, R. (2020). Factors influencing the development of microbes in food. *Shanlax International Journal of Arts, Science and Humanities, 7*(3), 57–77.
Rakhmanova, A., Khan, Z. A., & Shah, K. (2018). A mini review fermentation and preservation: role of lactic acid bacteria. *MOJ Food Processing Technology, 6*(5), 414–417.
Rashidi, L., & Khosravi-Darani, K. (2011). The applications of nanotechnology in food industry. *Critical Reviews in Food Science and Nutrition, 51*(8), 723–730.
Sandoval-Castilla, O., Lobato-Calleros, C., Aguirre-Mandujano, E., & Vernon-Carter, E. J. (2004). Microstructure and texture of yogurt as influenced by fat replacers. *International Dairy Journal, 14*(2), 151–159.
Sarkar, P., Abedin, M. M., Singh, S. P., Pandey, A., & Rai, A. K. (2022). Microbial production and transformation of polyphenols. In *Current developments in biotechnology and bioengineering* (pp. 189–208). Elsevier.
Shepherd, R., Rockey, J., Shutherland, I. W., & Roller, S. (1995). Novel bioemulsifiers from microorganisms for use in foods. *Journal of Biotechnology, 40*, 207–217.
Silbir, S., & Goksungur, Y. (2019). Natural red pigment production by *Monascus purpure*us in submerged fermentation systems using a food industry waste: brew spent grain. *Food, 8*(5), 161.
Singh, J. S., Abhilash, P. C., & Gupta, V. K. (2016). Agriculturally important microbes in sustainable food production. *Trends in Biotechnology, 34*(10), 773–775.
Singh, A. V., Hosseinidoust, Z., Park, B. W., Yasa, O., & Sitti, M. (2017a). Microemulsion-based soft bacteria-driven microswimmers for active cargo delivery. *ACS Nano, 11*(10), 9759–9769.
Singh, T., Shukla, S., Kumar, P., Wahla, V., Bajpai, V. K., & Rather, I. A. (2017b). Application of nanotechnology in food science: perception and overview. *Frontiers in Microbiology, 8*, 1501.
Soomro, A. H., Masud, T., & Anwaar, K. (2002). Role of lactic acid bacteria (LAB) in food preservation and human health-a review. *Pakistan Journal of Nutrition, 1*(1), 20–24.
Sridhar, A., Ponnuchamy, M., Kumar, P. S., & Kapoor, A. (2021). Food preservation techniques and nanotechnology for increased shelf life of fruits, vegetables, beverages and spices: a review. *Environmental Chemistry Letters, 19*(2), 1715–1735.
Teniola, O. D., Holzapfel, W. H., & Odunfa, S. A. (2022). Selection, use and the influence of starter cultures in the nutrition and processing improvement of 'ogi'.
van der MJEC, M., van der Veen, B., Uitdehaag, J. C. M., Leemhuis, H., & Dijkhuizen, L. (2002). Properties and applications of starch-converting enzymes of the α-amylase family. *Journal of Biotechnology, 94*, 137–155.
Wang, C., Liwei, M., Park, J. B., Jeong, S. H., Wei, G., Wang, Y., & Kim, S. W. (2018). Microbial platform for terpenoid production: Escherichia coli and yeast. *Frontiers in Microbiology, 9*, 2460.
Wasilewska, E., Zlotkowska, D., & Wroblewska, B. (2019). Yogurt starter cultures of Streptococcus thermophilus and lactobacillus bulgaricus ameliorate symptoms and modulate the immune response in a mouse model of dextran sulfate sodium-induced colitis. *Journal of Dairy Science, 102*(1), 37–53.

Weatherholtz, W. M., & Holsing, G. C. (1975). Evaluation of Torula yeast for use as a food supplement. *Federation Proceedings, 34*, 890.

Wesley, S. J., Raja, P., Raj, A. A., & Tiroutchelvamae, D. (2014). Review on-nanotechnology applications in food packaging and safety. *International Journal of Engineering Research, 3*(11), 645–651.

Yerlikaya, O., Akpinar, A., Saygili, D., & Karagozlu, N. (2020). Incorporation of Propionibacterium shermanii subsp. freudenreichii in probiotic dairy drink production: physicochemical, rheological, microbiological and sensorial properties. *International Journal of Dairy Technology, 73*(2), 392–402.

Zdolec, N., Lorenzo, J. M., & Ray, R. C. (2018). Use of microbes for improving food safety and quality. *BioMed Research International, 2018*, 3902698.

Zhang, B., Xu, L., Ding, J., Wang, M., Ge, R., Zhao, H., & Fan, J. (2022). Natural antimicrobial lipopeptides secreted by bacillus spp. and their application in food preservation, a critical review. *Trends in Food Science Technology, 127*, 26.

Zhao, G., Liu, C., Li, S., Wang, X., & Yao, Y. (2020). Exploring the flavor formation mechanism under osmotic conditions during soy sauce fermentation in aspergillus oryzae by proteomic analysis. *Food Function, 11*(1), 640–648.

Zhou, L., Zhao, X., Li, M., Yan, L., Lu, Y., Jiang, C., et al. (2021). Antibacterial and wound healing-promoting effect of sponge-like chitosan-loaded silver nanoparticles biosynthesized by iturin. *International Journal of Biological Macromol, 181*, 1183.

Zhu, Q., & Jackson, E. N. (2015). Metabolic engineering of *Yarrowia lipolytica* for industrial applications. *Current Opinion in Biotechnology, 36*, 65–72. https://doi.org/10.1016/j.copbio.2015.08.010