# **Open Access**

# Bioactive properties and therapeutic aspects of fermented vegetables: a review



Sadhisha Gunawardena<sup>1</sup>, Harshani Nadeeshani<sup>1</sup>, Vidun Amarasinghe<sup>2</sup> and Ruvini Liyanage<sup>1\*</sup>

# Abstract

The pathogenesis of non-communicable diseases (NCDs) worldwide is closely linked to the global nutrition transition. Functional foods play a crucial role in the prevention and control of NCDs, making them an active area of research. Fermentation, which involves the biotransformation of food, enhances its digestibility and nutritional properties by releasing bioactive molecules. The increased bioactivity during fermentation can be attributed to the liberation of compounds trapped in the food matrix, the generation of metabolites, or the metabolic products of the microorganisms involved. Additionally, fermented foods can serve as a vehicle to deliver live beneficial microbes to the gastrointestinal tract, promoting gut homeostasis. While most studies demonstrate an increase in bioactivity during fermentation, some investigations yield contradictory results, likely due to the complexity of the food matrix, microbial strains utilized, and environmental conditions during the fermentation process. Further research is needed to address conflicting findings, and epidemiological studies are recommended to examine the impact of fermented vegetables on human health. This review discusses changes in antioxidant, antidiabetic, antihyperlipidemic, anticancer, and antihypertensive activities of fermented vegetables, both in vitro and in vivo using animal models. Moreover, the drawbacks associated with vegetable fermentation, their management, and the future prospects of vegetable fermentation are also discussed.

Keywords Bioactivity, Non-communicable diseases, Fermented vegetables

\*Correspondence: Ruvini Liyanage ruvini.li@nifs.ac.lk Full list of author information is available at the end of the article



© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.



# Introduction

Non-communicable diseases (NCDs) are a significant class of health conditions responsible for deaths and disabilities worldwide. Each year, NCDs account for 74% of all global deaths, totalling 41 million deaths (Singer 2014). These diseases, including cardiovascular disease (CVD), cancer, chronic respiratory disease, diabetes, and kidney disease caused by diabetes, are strongly associated with factors like an unhealthy diet, physical inactivity, genetics, and environmental factors (Singer 2014). The prevalence of NCDs is closely linked to the global nutrition transition, characterized by reduced intake of fruits and vegetables and increased consumption of saturated fats, sugar, and alcohol. However, diet, weight maintenance, and physical activities play significant roles in preventing CVD, diabetes, and cancer (Puska 2002; Singer 2014; K.J. Li et al. 2022a, 2022b, 2022c). While drugs have been developed to mitigate the effects of nutrition-related risk factors in high-risk patients, changes in eating patterns have shown the potential in preventing or reducing the risk of NCDs, potentially reducing the need for medication (Singer 2014). Functional foods, which offer health benefits beyond basic nutrition, have emerged as a promising avenue for risk prevention and controlling NCDs (Hasler 2002).

In recent years, there has been a growing interest in exploring the potential health benefits of fermented foods. According to Marco et al. 2021, the definition of fermented foods and beverages can be elucidated as "foods made through desired microbial growth and enzymatic conversions of food components" (Marco et al. 2021). The fermentation process involves the activity of lactic acid bacteria (LAB) and fungi, such as yeast, with LAB fermenting carbohydrate substrates into lactic acid and yeast playing a vital role in popular fermented beverages, vegetables, and fruits (Adams & Moss 2007).

Fermented foods can be classified based on the initial fermentation substrate, including cereal-based, vegetable



Fig. 1 Antioxidant activity of some fermented vegetables

and fruit-based, dairy-based, fish and meat-based, and alcoholic or non-alcoholic beverages (Blandino et al. 2003; Terefe 2016). Further, the fermentations can be identified based on the major end products formed, such as alcoholic, lactic acid, acetic acid, alkali, butyric acid, mixed acid, and propionic acid (Sun et al. 2022). Among the diverse array of fermented foods, fermented vegetables have gained significant attention due to their unique bioactive properties and potential therapeutic effects Figs. 1, 2, 3, 4, 5, 6.

Food fermentation is a widely practiced technique that aims to extend the shelf life and improve the sensory properties of food compared to raw materials (Ciniviz & Yildiz 2020; Moslehi-Jenabian et al. 2010; Sivamaruthi et al. 2018; Verardo et al. 2020). Controlled growth of specific microbial strains during fermentation leads to desirable biochemical changes, the release of bioactive molecules, increased food digestibility, and enhanced nutrient bioavailability (Adebo et al. 2022; Chaves-López et al. 2014; Verardo et al. 2020). These bioactive molecules have been found to possess various health benefits, including antidiabetic, antihyperlipidemic, anticancer, and antihypertensive properties. Fermented foods also play a role in influencing gut health by promoting gut homeostasis and modulating gut microbiota (Marco et al. 2017). Moreover, fermentation contributes to the flavour and sensory quality of food through the breakdown of carbohydrates, lipids, and proteins into taste molecules and the production of volatile organic compounds (K R et al. 2022; Rajendran et al. 2023).

However, it is important to note that not all fermented foods have guaranteed shelf life or widespread acceptance due to the chemical nature of volatile organic compounds (VOCs) (Lu et al. 2022; Marco et al. 2017; Pang et al. 2018). VOCs contribute to the sensory properties of fermented food products; odour, flavour, and aftertaste (R. Li et al. 2022a, 2022b, 2022c). The potential impacts of VOCs on the safety and nutritional quality of these foods are still relatively unknown, making it difficult to definitively recommend the administration of fermented foods. Further research is required to gain a better understanding of the benefits and risks associated with VOCs in fermented foods in order to provide a more consistent recommendation. On the other hand fermented food can also pose potential food safety risks due to the presence of pathogenic microorganisms and microbial toxins such as biogenic amines, mycotoxins, and bacterial toxins (Fayyaz et al. 2022; Skowron et al. 2022; Spano et al. 2010). Therefore, appropriate measures should be taken to ensure the safety of fermented foods and minimize these risks.

Around 20% of the food consumed worldwide is estimated to be fermented, with a wide variety of fermented foods found in East-Asian, Indian, and African countries (Baruah et al. 2022; Varzakas et al. 2017). Vegetables are rich sources of beneficial compounds and are used to produce various fermented products. Fermentation of vegetables, such as cabbage, turnips, radishes, carrots, and others, dates back more than 2000 years and follows a simple procedure involving brine or dry salting and suitable storage conditions to allow spontaneous fermentation by naturally occurring LAB (Bährle-Rapp 2007; Di Cagno et al. 2013; Hayes & García-Vaquero 2016). Commercial-scale fermentation of vegetables includes



# Anti-diabetic Activity of Fermented Vegetables

Fig. 2 Anti-diabetic activity of fermented vegetables

cabbage, cucumber, and olives, while small-scale or household fermentation involves carrots, cauliflower, celery, okra, onions, peppers, and tomatoes (Adams & Moss 2007; Ciniviz & Yildiz 2020).

Although research related to fermented food is ongoing, consistent results can be challenging to obtain due to the complexity of food matrices and biochemical processes during fermentation. The roles of microorganisms, including probiotics, are crucial in conferring health benefits through fermented foods. In this review, we will discuss the bioactivities of fermented vegetables and the mechanisms behind their effects and the drawbacks associated with vegetable fermentation, their management, and the future prospects of vegetable fermentation.

# Antioxidant activity

Antioxidants are biochemically significant compounds, when present in lower concentrations, which can delay or prevent the oxidation of highly oxidisable substrates. Antioxidants in biological systems eliminate reactive oxygen species (ROS). The term ROS represents both free radical and non-free radical oxygenated molecules. During normal cellular metabolism, ROS are generated and play a vital role in stimulating signaling pathways in cells to respond accordingly to changes in intracellular and extracellular environments. The increased ROS formation or inefficient antioxidant activity (AOX) leads to an imbalance in ROS formation and the elimination of ROS hence leading to oxidative stress. The pathogenesis of oxidative stress has been confirmed to be a contributor to neurodegenerative diseases, emphysema, cardiovascular diseases, inflammatory diseases, cataracts, and cancer (Pisoschi & Pop 2015; Reuter et al. 2010).

Antioxidants present in vegetables are mostly phenolic compounds or polyphenols with important biological activities and pharmacological properties such as antiinflammatory, anticancer, antithrombotic, hepatoprotective and antiallergic properties. Polyphenols are classified based on their chemical structure, and four main groups have been identified: phenolic acids, flavonoids, stilbenes, and lignans. Among these compounds, flavonoids are the most abundant in plants and are often found in association with sugar molecules or in their glycosylated form



Fig. 3 Anti-diabetic activity of SCFA produced during vegetable fermentation

# Anti-hyperlipidemic Activity of Fermented Vegetables



Fig. 4 Anti-hyperlipidemic activity of fermented vegetables



Anticancer Activity of Fermented Vegetables

Fig. 5 Anticancer activity of fermented vegetables

(Maniglia et al. 2021). Microbial activity during fermentation hydrolyses these glycosylated forms into their aglycon/free forms which are more bioavailable than bound forms thereby contributing to increasing the AOX (Yeo & Ewe 2015). For instance, the fermentation of red pepper has increased its phenolic content, correspondingly increasing the DPPH radical scavenging activity. The increment probably attributes to the increased phenolic content (Yeon et al. 2019).

Similarly, carrot juice fermented with *Lactobacillus bulgaricus* and *Lacticaseibacillus rhamnosus* has increased DPPH radical scavenging activity (Table 1) in contrast to unfermented carrot juice (Yeo & Ewe 2015). Also, water extracts of immature *Graptopetalum paraguayense* E. Walther fermented with *Lactiplantibacillus plantarum* have increased both flavonoids, from 17.2 µg/mg to 22.9 µg/mg, and phenolic contents, from 92.2 µg/mg to 111 µg/mg (Wu et al. 2011).

Total phenolic content (TPC) and total flavonoid contents (TFC) of two Pakistani garlic varieties, desi raw garlic (DRG) and farmi raw garlic (FRG), were reported to increase during fermentation. Unfermented DRG was reported to have a TPC of 2421.27 mg GAE/kg and fermentation has increased the TPC to 2886.73 mg GAE/kg. FRG has shown the lowest TPC of 2128.52 mg GAE/kg. Similarly, the TPC of FRG increased from 2128.52 mg GAE/kg to 2529.82 mg GAE/kg during fermentation. The TFC of DRG was increased while fermentation from a value of 124 mg RE/100 g up to 191 mg RE/100 g and the TFC of FRG increased from 101 mg RE/100 g to 121 mg RE/100 g while fermenting. Fermentation also improved the DPPH scavenging activity of DRG from 36 to 54% and in FRG from 31 to 47%. Likewise, the ferric-reducing antioxidant power (FRAP) and ABTS radical scavenging activities increased during the fermentation process. From the results, it is evident that fermentation has improved the AOX of garlic (Tahir et al. 2022).

Singhal et al. (2021) reported that bamboo shoot fermentation (*Bambusa vulgaris*) shoots increased TPC and TFC from 29.0 to 42 mg GAE/100 g and 49.69 to 59.43 mg CE/100 g, respectively. The fermented bamboo shoots showed 2.13  $\mu$ mol TE/g compared to the fresh shoots, which were 1.72  $\mu$ mol TE/g when assayed by FRAP. It was also shown that an increase in free radical scavenging activity is proportional to TPC in the fraction. This suggests the contribution of phenolic acids to AOX (Singhal et al. 2021).

However, it should be noted that the phenolic content and AOX depend on the fermentation time. After a peak in TPC, TFC, and AOX, several investigations show a decrease in TPC, TFC, and AOX. For example,



# Antihypertensive Activity of Fermented Vegetables

Fig. 6 Antihypertensive activity of fermented vegetables

the effect of fermentation time on AOX was studied by Adetuyi & Ibrahim (2014). The results have shown that 24 h fermentation increases the phenolic content to 1460 mg GAE/100 g, while unfermented okra seeds only account for 185 mg GAE/100 g. TFC was also increased by 492.10% after 24 h of fermentation. Furthermore, the radical scavenging activity and ferric-reducing antioxidant power were enhanced after fermentation, with 24-h fermented seeds exhibiting the highest AOX. However, prolonged fermentation times (48 h and 72 h) result in the degradation of phenolic and flavonoid contents as well as antioxidant activities. This may be due to the oxidation of the compounds by several factors such as polyphenol oxidase activity, oxygen exposure, pH changes, temperature, and microbial activity (Adetuyi & Ibrahim 2014; Verni et al. 2019).

# Anti-diabetic activity

Diabetes is a non-communicable disease with 422 million people currently suffering worldwide. The disease is characterized by persistently elevated blood glucose levels above physiological limits. Among diabetes patients, type 2 diabetes (T2D) is the most prevalent and is caused by the gradual decrease in insulin activity and progressive impairment of insulin secretion by pancreatic  $\beta$ -cells. The low AOX in the pancreas increases its susceptibility to oxidative stress resulting in  $\beta$ -cell dysfunction. Researchers have reported that several functional foods can prevent or manage diabetes. The cost of insulin treatments, side effects caused by medications, and limited accessibility to treatments have made functional food an alternative method of prevention and management of T2D (Islam & Choi 2009; Uuh-Narvaez and Segura-Campos 2021). Several vegetable-based fermented foods were investigated for their activity in the prevention and management of diabetes.

Fermentation of vegetables under microbial influence increases the content of organic acids such as ascorbic acid, acetic acid, lactic acid, and succinic acid. Fermentation of cabbage (*Brassica oleracea* var. *capitata*) with *Lactiplantibacillus plantarum* (Table 1) for 12 days has been reported to exhibit changes in nutritional properties compared to raw cabbage (Uuh-Narvaez and Segura-Campos 2021). Acetic acid has been reported to suppress *disaccharidase* activity and increase glucose-6-phosphate concentrations in skeletal muscles, improving postprandial insulin sensitivity in insulin-resistant individuals (Johnston et al. 2004). A study was done to investigate the effect of pickled chilli pepper (*Capsicum frutescens* L.) towards inhibition of  $\alpha$ -glucosidase (an exo-type enzyme in the small intestine that can hydrolyze either mono-glycosides into free sugar and aglycone, or disaccharides into monosaccharides from the non-reducing end (Ikeda & Takahashi 2007)), and DPP-IV. It was shown that the concentration of flavonoid, luteolin, found in chilli pepper was significantly increased after fermentation and has shown the highest  $\alpha$ -glucosidase inhibition activity in vitro. In addition, another phytochemical found in pickled pepper, known as isorhamnetin 3-O-glucoside, has shown the highest inhibition capacity towards DPP-IV (M. Li et al. 2022a, 2022b, 2022c). However, in vivo studies should be conducted to confirm their activities.

Park et al. (2015) reported that the hot water or ethanol extracts of LAB-fermented bitter melon (*Momordica charantia*) significantly lowered blood-glucose levels of alloxan-induced diabetic mice (Park et al. 2015). In addition, it has also been shown to protect against alloxan monohydrate-induced liver damage and maintained low levels of triglycerides. This finding suggests the possibility of utilizing fermented bitter melon in the treatment of human diabetes.

Li et al. (2014) investigated the effect of Lactiplantibacillus plantarum fermented carrot juice on rats fed a high-fat diet and low-dose streptozotocin-induced type 2 diabetes. From the study, it was suggested that the fermented carrot juice supplement with Lactiplantibacillus plantarum for 5 weeks could regulate blood glucose and related hormones such as insulin, glucagon, GLP-1 (glucagon-like peptide-1), and PYY (YY peptide). Also, this has ameliorated diabetes-induced damage to the pancreas and kidneys. The significant increase in shortchain fatty acids (SCFA) in fermented carrot juice and the appearance of butyric acid in fermented carrot juice in contrast to the absence in non-fermented carrot juice suggests that Lactiplantibacillus plantarum can ferment dietary fibre. The rats fed with Lactiplantibacillus plantarum fermented carrot juice have shown higher levels of SCFA in the colonic faeces.

The SCFA has several physiological properties that might suppress diabetes by different pathways. Several studies have shown that SCFAs promote the secretion of GLP-1 and peptide YY, which increases the feeling of satiety through the gut-brain axis, indirectly reducing appetite and consequent food intake (Salamone et al. 2021) SCFAs are not only important in gut health and as signaling molecules, but they can enter into the systemic circulation and directly affect metabolism and other peripheral tissue functions (Canfora et al. 2015). When SCFAs enter the liver they have been shown to decrease glycolysis and gluconeogenesis while increasing glycogen synthesis and fatty acids oxidation. Additionally, SCFA improves glucose uptake in skeletal muscles and adipose tissue by increasing the expression of GLUT4, through AMP kinase activity. Moreover, the reduction of glycolysis rate by SCFA leads to accumulation glucose-6-phosphate in skeletal muscles, which in turn increases glycogen synthesis (Salamone et al. 2021). The ability of SCFA to lower intestinal pH by promoting the growth of lactobacilli and bifidobacteria is expected to have a beneficial effect on diabetes. Propionate, an SCFA, has been shown to decrease glucose production in rat hepatocytes. In addition, SCFA like butyric acid and propionic acid have been linked to increasing GLP-1 hormone, which lowers plasma glucose concentration and preserves pancreatic β-cell function (Li et al. 2014).

The effects of Morinda citrifolia (MC) and fermented Morinda citrifolia (FMC) in KK-Ay diabetic mice have been studied by Lee et al. 2012. The results show that FMC has stronger antidiabetic effects than unfermented MC. The FMC administered KK-Ay mice have shown far lower serum glucose levels. In addition, FMC supplement shown to reduce glycosylated hemoglobin (Hb1Ac) levels and improved insulin sensitivity (Lee et al. 2012). The enhanced insulin sensitivity attributes to the elevated glucose disposal rates in C2C12 myotubes via activation of PPAR-γ (peroxisome-proliferator activated receptor-γ), in which increase the insulin sensitization and enhance glucose metabolism (Tyagi et al. 2011) and AMPK, which stimulates glucose uptake in skeletal muscles (Jeon 2016; Lee et al. 2012). Several bioactive phytochemicals such as anthraquinones, flavonol glycosides and terpenoids present in MC and their increase during fermentation can be attributed for enhanced antidiabetic action of FMC (Lee et al. 2012).

Fermentation of the extract of purple Jerusalem artichoke with *Lactiplantibacillus plantarum* (LJA) was investigated for antidiabetic effect in non-insuline – dependent diabetes mellitus mice (*db/db* mice). The LJA has shown to reduce blood glucose levels and Hb1Ac levels in db/db mice and it is due to the secretion of pancreatic secretion of insulin. In addition, partial inhibition of  $\alpha$ -glucosidase activity small intestine and significant inhibition of sucrase and lactase contribute to the prevention of increase in postprandial glucose levels in blood (Wang et al. 2016).

# Anti-hyperlipidemic activity

An increase in total serum cholesterol, triglycerides, and low-density lipoproteins (LDL) along with a decrease in high-density lipoproteins (HDL) known as hyperlipidemia. The increased lipid levels could result in atherosclerosis. In addition, elevated triglycerides associate

#### Vegetable/Product Microorganism **Mechanism of Action** References Antioxidant Activity Red pepper Increase phenolic compounds Yeon et al. 2019 Increased DPPH radical scavenging activity Increased DPPH scavenging activity Carrot Juice L. bulgaricus and Yeo & Ewe 2015 L. rhamnosus Graptopetalum paraguayense E. Walther L. plantarum Increased TPC and TFC Wu et al. 2011 Garlic (desi and farmi varieties) Increased TPC and TEC Tahir et al. 2022 Increased DPPH, FRAP and ABTS Increased TPC and TFC Bamboo Singhal et al. 2021 Increased FRAP Okra Increase TPC and TFC (24 h) Adetuyi & Ibrahim 2014 Increased DPPH Anti-diabetic Activity Cabbage L. plantarum Suppress disaccharidase activity Johnston et al. 2004; Uuh-Narvaez & Segura-Campos 2021 Chili pepper a-glucosidase inhibition M. Li et al. 2022a, 2022b, 2022c DPP-IV inhibition Bitter melon LAB Lower blood glucose levels of alloxan-H. S. Park et al. 2015 induced diabetes mice Carrot Juice L. plantarum Regulate levels of insulin, glucagon, GLP-1 C. Li et al. 2014 and Peptide YY SCFA lowering intestinal pH SCFA Anti-hyperlipidemic Activity Fermented cabbage/Kimchi Regulation of 3-hydroxy-methyl-glu-I. H. Choi et al. 2013 taryl-CoA reductase, cholesterol ester transferase protein and cholesterol acyltransferase β-Sitosterol . HDMPPA Bamboo shoots Increase availability of β-Sitosterol Lu et al. 2009 Singhal et al. 2021 Moringa Decrease fat accumulation in rat liver Joung et al. 2017 Decrease expression of lipid synthetic aenes Up-regulation the expression of genes related to lipid oxidation Spinach Acetobacter xvlinum Inhibition of porcine pancreatic lipase Marvati et al. 2020 Brocilli Glukonobacter Zhu et al. 2021 Katuk leaves S. cerevisiae Suppress lipid accumulation Y. M. Choi & Suh 2004 Dobiásová 2006 Red pepper Reduce plasma TG and TC Kawada et al. 1986 Decrease artherogenic index Stimulate lipid mobilization from adipose tissue Traditional Chinese fermented cucum-L. acidophilus Reduction of TC, TG and LDL-C in rat serum Gao & Li 2018 Enterococcus faecalis Reduction of TC and TG in rat liver ber Anticancer Activity White cabbage/Sauerkraut L. mesenteroides Attenuate oxidative stress and inflam-Martinez-Villaluenga et al. 2012 matkon Hur et al. 1999 Cabbage/Kimchi Inhibition growth of HT-29 carcinoma cells Inhibition survival and growth of MG-63, K. Y. Park et al. 2014 HL-60 and Hep 3B cells Inhibit incorporation of H thymidine decreasing DNA synthesis β-sitosterol and a linoleic acid Kazimierczak et al. 2014 Beetroot Induce apoptosis and necrosis Cinnamon L. plantarum Decrease cancer cell viability Eweys et al. 2022

# Table 1 Summary of bioactivity and mechanism of action

Table 1	(continued)
---------	-------------

Vegetable/Product	Microorganism	Mechanism of Action	References
Anti-hypertensive Activity			
Cucumber	LAB	ACE inhibition via peptides IPP/LPP, VPP, KP and RY	Fideler et al. 2019
Spinach juice	L. brevis L. sakei	ACE inhibition via peptides IVVGPPPP, PQTETKASVGFKAG and QIIGPVLD	M. J. Kim et al. 2022

Abbreviations: DPPH 2,2-diphenyl-1-picrylhydrazyl, TPC Total phenolic content, TFC Total flavonoid content, FRAP Ferric reducing antioxidant power, ABTS (2,2'-azinobis(3-ethylbenzothiazoline-6-sulfonic acid)), DPP-IV Dipeptidyl peptidase IV, GLP-1 Glucagon like peptide-1, SCFA Short chain fatty acids, HDMPPA 3-(4'-Hydroxyl-3',5'dimethoxyphenyl)propionic acid, TG Triglyceride, TC Total cholesterol, LDL-C Low density lipoproteins cholesterol, ACE Angiotensin-1- converting enzyme

with acute pancreatitis. The reduction in total serum cholesterol by 10% shows a 15% reduction in coronary heart disease mortality (Eaton 2005; Jain et al. 2007). Hyperlipidemia is a risk factor for lipid accumulation and inflammation of the large arteries, also known as atherosclerosis. The accumulation of certain plasma lipoproteins, low-density lipoproteins, and remnants of triglyceride-rich lipoproteins in the intimal region of the vessel initiates atherosclerosis (Björkegren & Lusis 2022; Saldera et al. 2017). A major risk factor for coronary heart disease is elevated cholesterol in the blood, which could also induce colon cancer. Certain strains such as Lactobacillus acidophilus possess the ability to reduce cholesterol by cholesterol degradation, cholesterol oxidase activity, and bile salt hydrolase activity. The presence of LAB in fermented vegetables could be beneficial for human health by reducing cholesterol levels.

Kimchi, a salted fermented cabbage, has been shown to lower the levels of triglycerides, total cholesterol (TC), and LDL-cholesterol (LDL-C) in the plasma of high-cholesterol diet-fed rats. In addition, a kimchi diet has been shown to suppress the cholesterol accumulation in the aortic tissue of rabbits fed with a high-cholesterol diet, by reducing plasma TC and LDL-C levels. A study done by In Hwa Choi et al. 2013, have pointed out two important observations. Firstly, despite the quantity of kimchi intake there were improved serum lipid profiles and antioxidant levels, and secondly, a high quantity of kimchi intake impose a beneficial effect on serum total cholesterol concentration (Choi et al. 2013). Regulation of the activities of 3-hydroxy-3-methyl-glutaryl-CoA reductase, cholesterol ester transferase protein, and cholesterol acyl-transferase activities in the liver of rabbits and rats exerts hypolipidemic effects.

The administration of organic acids such as 3-(4'-Hydroxyl-3',5'-dimethoxyphenyl) propionic acid (HDMPPA), which was isolated from dichloromethane extracts of fermented Korean kimchi, has lowered plasma cholesterol levels in hypercholesterolemic rabbits. The active compound HDMPPA is supposed to be produced by microbes during fermentation, inhibits LDL oxidation

and promotes free radical scavenging activity (Choi et al. 2013; Hyun et al. 2007).

Phytosterols are bioactive compounds that occur in all vegetables and represent the major part of the nonsaponifiable fraction of lipids. During fermentation, not only do phenolic compounds increase due to the removal of the glycosidic part, but there are also changes in sterols that contribute to their increase in bioactivity. Sterols, such as  $\beta$ -sitosterol and campesterol, are commonly found in plant-based foods and have been associated with various health benefits, including their cholesterollowering properties (Blanco-Morales et al. 2021a, 2021b) Sterols are structurally similar to cholesterol. Therefore, sterols can compete with the absorption of cholesterol to lower serum cholesterol levels in humans and prevent the risk of cardiovascular disease (Lu et al. 2009) making sterols a beneficial component in the human diet.

Fresh and fermented bamboo shoots have several sterol compounds including  $\beta$ -sitosterol, campesterol and stigmasterol. The dry weight of the sterol content in fermented bamboo shoots was reported to increase from 0.19% to 0.44% in Dendrocalamus hamiltonii and from 0.12% to 0.62% in Bambusa balcooa compared to unfermented fresh shoots. Fermentation processes, particularly those involving microorganisms like lactic acid bacteria, can lead to the conversion of sterols into their more bioactive forms, such as their corresponding esters. This conversion occurs through the enzymatic activity of the microorganisms, resulting in the release of free sterols from their esterified forms. The increased bioactivity of sterols during fermentation can be attributed to the liberation of these free sterols, which are more readily absorbed by the human body. Several studies have demonstrated the enhancement of sterol content and bioavailability in fermented foods, highlighting the potential of fermentation to improve the nutritional properties and health benefits of plant-based ingredients. (Blanco-Morales et al. 2021a, 2021b). Studies have reported that bamboo shoots can significantly reduce serum total cholesterol and LDL cholesterol levels in rats (Lu et al. 2009; Singhal et al. 2021).  $\beta$ -Sitosterol also found in kimchi can

compete with the absorption of cholesterol in the intestine (Kim et al. 2018).

Methanolic extracts of *Moringa oleifera* were subjected to fermentation by three strains of Lactobacillus, and the beneficial effect on hepatic steatosis (fatty liver disease) was examined in high-fat diet-induced obese mice. The results were compared with supplementation of nonfermented *M. oleifera* extract. Fermented moringa supplementation in mice fed with a high-fat diet has been shown to decrease the accumulation of fat in the liver. The fermented extract has been shown to decrease the expression of multiple genes related to lipid synthesis and up-regulated the expression of genes related to lipid oxidation (Joung et al. 2017). The results suggest that fermented *M. oleifera* supplement could be an effective treatment for nonalcoholic fatty liver.

Kombucha starting culture consisting of Acetobacter xylinum, Gluconobacter, and Saccharomyces cerevisiae was used to ferment filtrates of spinach (Amaranthus spp.), broccoli (Brassica oleraciea L.) and katuk leaves (Sauropus androgynous). Among the vegetable extracts, katuk leaves extract showed the highest porcine pancreatic lipase inhibition activity of 91.44% after fermenting for 6 days while spinach leaves extract showed its highest inhibitory activity of 28.41% after 12 days of fermentation. As the pancreatic lipase enzyme is critical in the digestion and absorption of dietary lipids, it is significant in controlling obesity and serum lipid levels. Polyphenols and flavonoids are known to inhibit pancreatic lipase thereby slowing-down the absorption of triacylglycerol, increase excretion of cholesterol and inhibit secretion apolipoprotein B100. Furthermore, flavonoids can reduce LDL cholesterol and triglyceride levels by increasing the activity of lipoprotein lipase enzyme. Also, flavonoids reported to reduce cholesterol levels in blood by inhibiting HMG CoA reductase (Maryati et al. 2020). The study observed that the duration of fermentation is a factor affecting the lipase inhibitory activity (Maryati et al. 2020; Zhu et al. 2021). During the fermentation process active compounds in vegetables degrade and produce other bioactive compounds like flavonoids (Maryati et al. 2020) and the subsequent oxidation by the action of polyphenol oxidase (Adetuyi & Ibrahim 2014) responsible for depletion of bioactivity.

Rats fed a high-fat diet control (HF-C) and a high-fat diet along with 0.25 mL of fermented red pepper (*Capsicum annuum*) (HF-S) for 3 weeks showed a significant difference in the perirenal fat pads. However, there were no significant differences between the HF-C and 0.15 mL HF-S groups. This shows that the administration of fermented red pepper can suppress lipid accumulation in a dose-dependent manner. HF-S 0.25 mL and 0.10 mL HF-S were also shown to reduce plasma levels of TG and

TC compared to HF-C rats. The logarithmic ratio of triglyceride molar concentration to HDL-C or atherogenic index was decreased with the addition of fermented red pepper (Choi & Suh 2004; Dobiásová 2006). Capsaicin, *N*-(4-hydroxy-3-methoxy-benzyl)-8-methylnon-*trans*-6-enamide, has shown to lower serum triglycerides. The activity of hepatic enzymes, glucose-6-phosphate dehydrogenase and adipose lipoprotein lipase were higher when the diet was supplemented with capsaicin. The findings suggest that capsaicin stimulate lipid mobilization from adipose tissue and lowers the perirenal adipose tissue weight and serum triglyceride concentration in rats fed with high fat diet (Kawada et al. 1986).

Rats that were fed a high-lipid diet supplemented with Lactobacillus acidophilus and Enterococcus faecalis strains, which were isolated from traditional Chinese fermented cucumber, showed low serum lipid levels. Rats that were supplemented with Enterococcus faecalis showed a 31.3%, 26.8% and 40.8% reduction in serum TC, TG, and LDL-C respectively. Lactobacillus acidophilus decreased serum LDL-C levels in rats by 34.2%. Furthermore, the serum HDL-C was not significantly decreased by either strain. TC and TG levels in the rat liver were decreased by 30.2% and 21.6% in Lactobacillus acidophilus and 33.9% and 34.6% in Enterococcus faecalis, respectively. Additionally, the faeces of rats supplemented with LAB, contained greater amounts of bile acids which helped to maintain lower serum and liver cholesterol levels (Gao & Li 2018).

# Anticancer activity

The uncontrolled growth of abnormal cells in any organ or tissue is known as cancer which can originate in any part of the body subsequently invading adjoining organs and tissues (metastasis). According to the World Health Organization (WHO), cancer is the second leading cause of death with an estimate of 9.6 million deaths in 2018. The use of tobacco, alcohol consumption, and an unhealthy diet increase the risk of cancer.

The imbalance between ROS formation and quenching results in oxidative stress in biological systems. Prolonged ROS production significantly damage cellular structure and functions and may induce somatic mutations and neoplasia. The pathogenesis of cancer is linked to oxidative stress as it increases the DNA mutations or inducing DNA damage, genome instability and cell proliferation (Martinez-Villaluenga et al. 2012; Reuter et al. 2010).

Today, chemotherapy is used as the standard treatment for cancer. The non-specificity of chemotherapeutic agents imposes side effects and limits the optimal use of this therapy. Despite chemotherapy, functional foods can play a role in prophylaxis of the disease. From epidemiological and in vivo studies, it is evident that dietary intake of antioxidants and anti-inflammatory compounds can lower oxidative stress and inflammation (Martinez-Villaluenga et al. 2012).

However, the role of fermented food in the prevention of cancer is still debatable, as several studies suggested that the consumption of fermented food reduces the risk of cancer while some studies suggested that there is no strong relationship in reducing cancer. Anticancer activity of food can take several mechanisms, such as induction of apoptosis, inhibition of cell proliferation, activation of tumor suppression genes, and by protecting healthy cells via anti-inflammatory and antioxidative activity (Kesika et al. 2022). Several in vitro studies done to assess the anticancer activity of fermented vegetablebased foods are reviewed.

Fermentation of white cabbage with LAB was used to make sauerkraut in central Europe. During fermentation, the enzyme hydrolysis of glucobrassicin into indol-3-carbinol and its subsequent condensation with L-ascorbic acid form ascorbigen. In vitro studies have shown that ascorbigen acts as a moderate free radical scavenger and as a potential inhibitor of chemical-induced lipid peroxidation in human keratinocytes. Furthermore, ascorbigen has been shown to moderately inhibit NO in LPS (lipopolysachcharides) - induced mouse peritoneal macrophage. Fermentation and use of Lactobacillus mesen*teroides* as a starter culture has improved the ascorbigen content, antioxidant capacity, and NO production inhibitory activities. The data showed a 12-fold increase in ascorbigen content, a twofold increase in oxygen radical absorbance capacity, and 2.6 fold increment in NO production inhibitory potential. Data suggest the potential of sauerkraut to attenuate oxidative stress and inflammation (Martinez-Villaluenga et al. 2012).

Taking into account the duration of the fermentation of kimchi, it has been divided into four stages based on acidity. The stages are initial stage, immature stage, optimum-ripening stage and over-ripening stage. The effect of kimchi fermentation duration was determined in HT-29 colon carcinoma cells. The results showed that kimchi in the optimal ripening stage inhibits carcinoma cell growth by 54.3% while fresh and over ripened stages shown 39.6% and 49% respectively (Hur et al. 1999). In addition, there was the survival and growth of MG-63 osteocarcinoma, HL-60 leukemia and Hep 3B liver cancer cells were inhibited by kimchi extracts in sulforhodamine B assay, MTT assay, and growth inhibition test. Kimchi dichloromethane extracts were reported to inhibit the incorporation of <sup>3</sup>H thymidine into cancer cells decreasing the DNA synthesis of cancer cells (Hur et al. 1999; Park et al. 2014). In addition, the dichloromethane fraction induced apoptosis of HL-60 human leukemia cells. The main anticancer activity was shown by the active compounds  $\beta$ -sitosterol and a linoleic acid derivative present in kimchi (Park et al. 2014).

The effect of organic and conventional fermented beetroot (*Beta vulgaris* L.) juice in gastric adenocarcinoma (AGS) cells was studied by Kazimierczak et al. (2014). The results showed that extracts of organic beetroot (Grown without using pesticides and artificial fertilizers) juices have induced higher levels of late apoptosis and necrosis in AGS cells in vitro. In contrast, conventional extracts caused a higher level of early apoptosis. The response of the AGS cells was also shown to influence by different concentrations of the extracts, i.e. 0.05% extract concentration was observed to induce significantly higher early apoptosis in comparison to the other concentrations 0.025% and 0.0125% (Kazimierczak et al. 2014).

The fermentation of extracts of cinnamon using the probiotic bacterium *Lactiplantibacillus plantarum* has shown increased anticancer activity. Fermented extracts have been shown to decrease cancer cell viability compared to unfermented cinnamon extracts. Fermentation was also shown to improve the viability of normal cells, making it a promising source of anticancer agent without toxic effect (Eweys et al. 2022).

# Anti-hypertensive activity

Hypertension is a condition in which blood vessels have persistently elevated pressure. It carries a high risk factor for atherosclerosis, stroke, myocardial infarction, and end-stage renal disease. According to the WHO, 1.28 billion adults aged 30–79 worldwide have hypertension. Unhealthy diets, physical inactivity, tobacco and alcohol consumption, and obesity are risk factors.

Angiotensin-I-converting enzyme (ACE) catalyzes the conversion of angiotensin I to angiotensin II, which is a potential vasoconstrictor that ultimately elevates arterial pressure. Also ACE catalyze the degradation of vasodilator, bradykinin. Inhibition of ACE activity can decrease the concentration of angiotensin II concentration and increase bradykinin resulting in low blood pressure.

LAB-fermented cucumber analysis has shown to contain five types of peptides, IPP/LPP, VPP, KP, and RY. It was reported that during fermentation peptides IPP/ LPP and VPP were formed and peptide KP was enhanced compared with acidified cucumber. From previous studies, it has been reported that KP, RY, and LPP are potential antihypertensive peptides. In addition, IPP/ LPP and VPP are ACE inhibitory peptides and have been extensively studied in human trials and meta-analysis data suggest that diets containing these peptides can produce a slight but clinically significant hypotensive effect (Fideler et al. 2019). Spinach juice co-fermented with *Levilactobacillus brevis* and *Latilactobacillus sakei* (Table 1) has shown an increase in ACE inhibitory activity. The fermentation process has produced IVVGPPPP, PQTETKASVGFKAG, and QIIGPVLD peptides and has shown a positive correlation with the inhibitory activity. This suggests the fermentation of spinach with mentioned microorganisms may have the potential for hypertension management (Kim et al. 2022).

# Drawbacks in vegetable fermentation and their management

While fermented vegetables offer promising bioactive properties and potential health benefits, it is important to acknowledge and address certain drawbacks in their fermentation process and management. One common drawback is the risk of spoilage due to the growth of harmful bacteria or molds (Ray & Joshi 2014). To manage this, it is crucial to ensure proper hygiene and sanitation throughout the fermentation process, including cleaning equipment and using clean, high-quality vegetables. Additionally, maintaining the correct temperature and pH levels, as well as using reliable starter cultures, can help promote the growth of beneficial microorganisms while inhibiting the growth of pathogens (Wacher et al. 2010). Another challenge is the variability in fermentation outcomes, as factors like temperature fluctuations or inconsistent starter culture activity can result in inconsistent flavors and textures. Consistent monitoring, documentation, and adjustment of fermentation times and conditions can help address this issue, ensuring more predictable and desirable outcomes (Marco et al. 2017). Lastly, managing the risk of excessive fermentation can help prevent overly sour or mushy vegetables. Regular sensory evaluation and adherence to recommended fermentation times are important to strike the right balance and achieve the desired flavor and texture in fermented vegetables. By proactively addressing these drawbacks through careful management and monitoring, vegetable fermentation can be a successful and safe process for producing highquality fermented products.

# Future perspectives of vegetable fermentation

The future perspectives on vegetable fermentation hold immense potential for transforming the approach to vegetable consumption and food sustainability. As society progresses towards a more plant-centric diet and seeks innovative solutions to reduce food waste, vegetable fermentation emerges as a powerful tool. Advanced fermentation techniques specifically tailored to vegetables are expected to be developed in the coming years, enabling the preservation of flavors, textures, and nutritional value for extended periods. This presents an array of opportunities for creating diverse fermented vegetable products that cater to various tastes and dietary preferences, ranging from kimchi and sauerkraut to pickles and fermented vegetable-based condiments. Furthermore, vegetable fermentation contributes to sustainability by mitigating food waste, utilizing surplus or imperfect vegetables that would otherwise be discarded, thereby reducing strain on resources and promoting a circular economy (Ganesh et al. 2022; Hegde & Trabold 2018). Moreover, fermentation enhances the bioavailability of nutrients in vegetables, improving digestibility and amplifying their health benefits (Farhad et al. 2010). Anticipated to gain popularity in the future, vegetable fermentation will likely be embraced by both consumers and the food industry due to its delectable flavors, health advantages, and eco-friendly nature.

# Conclusion

Food fermentation, a method utilized since ancient times for food preservation, has evolved to encompass the realm of functional foods that offer health benefits beyond basic nutrition. The bioactive properties of fermented vegetables present a promising avenue for research in the treatment of non-communicable diseases. Numerous studies have demonstrated encouraging results regarding the bioactivity of fermented vegetables, both in vitro and in vivo using animal models. However, it is essential to acknowledge the existence of contrasting findings within the limited body of research available. It is worth noting that the current investigations merely indicate the potential bioactivity of fermented vegetables in promoting human health, and scientific evidence substantiating their benefits in humans' remains lacking. Consequently, it is crucial to conduct epidemiological studies in this field to establish and confirm the advantages of fermented foods for human well-being. Additionally, effectively managing the drawbacks associated with vegetable fermentation, such as hygiene, sanitation, temperature control, and starter culture selection, is essential for optimizing the production of fermented vegetables. By addressing these challenges, high-quality, safe, and beneficial fermented products can be achieved, contributing to a healthy lifestyle and preventive healthcare strategies. Future research efforts should aim to fill these gaps in knowledge, providing robust evidence to support the integration of fermented vegetables into a healthy lifestyle and preventive healthcare strategies.

### Acknowledgements

Not Applicable.

# Author's contribution

Ruvini Liyanage designed, reviewed, and revised the article. Sadisha Gunawardena, Harshani Nadeeshani, and Vidun Amarasinghe wrote the manuscript. All authors contributed to the article and approved the submitted version.

#### Funding

Not Applicable.

# Availability of data and materials

Not Applicable.

# Declarations

**Ethics approval and consent to participate** Not Applicable.

#### **Consent for publication**

Not Applicable.

#### **Competing interests**

We have no conflicts of interest in disclosing the content of this paper.

#### Author details

<sup>1</sup>Nutritional Biochemistry Program, National Institute of Fundamental Studies, Hantana Rd, Kandy 20000, Sri Lanka. <sup>2</sup>The King's School, Moss Vale, NSW, Australia.

# Received: 27 January 2023 Accepted: 12 June 2023

## References

- Adams, M. R., & Moss, M. O. (2007). Food Microbiology. The Royal Society of Chemistry. https://doi.org/10.1039/9781847557940
- Adebo, J. A., Njobeh, P. B., Gbashi, S., Oyedeji, A. B., Ogundele, O. M., Oyeyinka, S. A., & Adebo, O. A. (2022). Fermentation of Cereals and Legumes: Impact on Nutritional Constituents and Nutrient Bioavailability. *Fermentation.*, 8(2), 1–57. https://doi.org/10.3390/fermentation8020063
- Adetuyi, F. O., & Ibrahim, T. A. (2014). Effect of Fermentation Time on the Phenolic, Flavonoid and Vitamin C Contents and Antioxidant Activities of Okra (Abelmoschus esculentus) Seeds. *Niger Food J, 32*(2), 128–137. https://doi.org/10.1016/s0189-7241(15)30128-4
- Bährle-Rapp M. 2007. Fermented Vegetable. In: Springer Lex Kosmet und Körperpfl. Berlin, Heidelberg: Springer Berlin Heidelberg; p. 203–203. https://doi.org/10.1007/978-3-540-71095-0\_3943
- Baruah, R., Ray, M., & Halami, P. M. (2022). Preventive and therapeutic aspects of fermented foods. J Appl Microbiol, 132(5), 3476–3489. https://doi.org/10. 1111/jam.15444
- Björkegren, J. L. M., & Lusis, A. J. (2022). Atherosclerosis: Recent developments. *Cell*, 185(10), 1630–1645. https://doi.org/10.1016/j.cell.2022.04.004
- Blanco-Morales V, Garcia-Llatas G, Yebra MJ, Sentandreu V, Alegría A. 2021a. In vitro colonic fermentation of a plant sterol-enriched beverage in a dynamic-colonic gastrointestinal digester. LWT. 145:111273. https://doi. org/10.1016/j.lwt.2021.111273
- Blanco-Morales V, Garcia-Llatas G, Yebra M J, Sentandreu V, Alegria A. 2021b. In vitro colonic fermentation In vitro colonic fermentation of a plant sterol-enriched beverage in a dynamic-colonic gastrointestinal digester. *LWT - Food Sci. Technol.* 145. https://doi.org/10.1016/j.lwt.2021.111273
- Blandino, A., Al-Aseeri, M. E., Pandiella, S. S., Cantero, D., & Webb, C. (2003). Cereal-based fermented foods and beverages. *Food Res Int*, 36(6), 527–543. https://doi.org/10.1016/S0963-9969(03)00009-7
- Canfora, E. E., Jocken, J. W., & Blaak, E. E. (2015). Short-chain fatty acids in control of body weight and insulin sensitivity. *Nat Rev Endocrinol*, *11*(10), 577–591. https://doi.org/10.1038/nrendo.2015.128
- Chaves-López, C., Serio, A., Grande-Tovar, C. D., Cuervo-Mulet, R., Delgado-Ospina, J., & Paparella, A. (2014). Traditional Fermented Foods and

Beverages from a Microbiological and Nutritional Perspective: The Colombian Heritage. *Compr Rev Food Sci Food Saf, 13*(5), 1031–1048. https://doi.org/10.1111/1541-4337.12098

- Choi, Y. M., & Suh, H. J. (2004). Pharmacological effects of fermented red pepper. *Phyther Res*, *18*(11), 884–888. https://doi.org/10.1002/ptr.1490
- Choi, I. H., Noh, J. S., Han, J. S., Kim, H. J., Han, E. S., & Song, Y. O. (2013). Kimchi, a Fermented Vegetable, improves serum lipid profiles in healthy young adults: Randomized clinical trial. *J Med Food*, *16*(3), 223–229. https://doi. org/10.1089/jmf.2012.2563
- Ciniviz, M., & Yildiz, H. (2020). Determination of phenolic acid profiles by HPLC in lacto-fermented fruits and vegetables (pickle): Effect of pulp and juice portions. J Food Process Preserv, 44(7), 1–11. https://doi.org/10.1111/jfpp.14542
- Di Cagno, R., Coda, R., De Angelis, M., & Gobbetti, M. (2013). Exploitation of vegetables and fruits through lactic acid fermentation. *Food Microbiol*, 33(1), 1–10. https://doi.org/10.1016/j.fm.2012.09.003
- Dobiásová M. 2006. [AIP--atherogenic index of plasma as a significant predictor of cardiovascular risk: from research to practice]. Vnitr Lek. 52(1):64–71. http://www.ncbi.nlm.nih.gov/pubmed/16526201
- Eaton, C. B. (2005). Hyperlipidemia. *Prim Care Clin off Pract., 32*(4), 1027–1055. https://doi.org/10.1016/j.pop.2005.09.002
- Eweys AS, Zhao YS, Darwesh OM. 2022. Improving the antioxidant and anticancer potential of Cinnamomum cassia via fermentation with Lactobacillus plantarum. Biotechnol Reports. 36(July):e00768. https://doi.org/ 10.1016/j.btre.2022.e00768
- Farhad, M., Kailasapathy, K., & Tamang, J. P. (2010). Health Aspects of Fermented Foods. In Fermented foods and beverages of the world (pp. 391–414). CRC Press. https://doi.org/10.1201/EBK1420094954-19
- Fayyaz K, Nawaz A, Olaimat AN, Akram K, Farooq U, Fatima M, Siddiqui SA, Rana IS, Mahnoor M, Shahbaz HM. 2022. Microbial toxins in fermented foods: health implications and analytical techniques for detection. J Food Drug Anal. 30(4):523–537. https://doi.org/10.38212/2224-6614.3431
- Fideler J, Johanningsmeier SD, Ekelöf M, Muddiman DC. 2019. Discovery and quantification of bioactive peptides in fermented cucumber by direct analysis IR-MALDESI mass spectrometry and LC-QQQ-MS. Food Chem. 271(March 2018):715–723. https://doi.org/10.1016/j.foodchem.2018.07.187
- Ganesh KS, Sridhar A, Vishali S. 2022. Utilization of fruit and vegetable waste to produce value-added products: Conventional utilization and emerging opportunities-A review. Chemosphere. 287:132221. https://doi.org/10. 1016/j.chemosphere.2021.132221
- Gao, Y., & Li, D. (2018). Screening of lactic acid bacteria with cholesterol-lowering and triglyceride-lowering activity in vitro and evaluation of probiotic function. *Annales De Microbiologie, 68*(9), 537–545. https://doi.org/10. 1007/s13213-018-1360-0
- Hasler, C. M. (2002). Functional foods: Benefits, concerns and challenges A position paper from the American Council on Science and Health. *J Nutr,* 132(12), 3772–3781. https://doi.org/10.1093/jn/132.12.3772
- Hayes M, García-Vaquero M. 2016. Bioactive Compounds from Fermented Food Products. Food Eng Ser:293–310. https://doi.org/10.1007/978-3-319-42457-6\_14
- Hegde S, Trabold TA. 2018. Sustainable Waste-to-Energy Technologies: Fermentation. In: Sustain Food Waste-To-energy Syst. [place unknown]: Elsevier; p. 69–88. https://doi.org/10.1016/B978-0-12-811157-4.00005-X
- Hur, Y.-M., Kim, S.-H., & Park, K.-Y. (1999). Inhibitory Effects of Kimchi Extracts on the Growth and DNA Synthesis of Human Cancer Cells. J Food Sci Nutr., 4(2), 107–112.
- Hyun, J. K., Jin, S. L., Hae, Y. C., Su, H. S., Suh, H., Jung, S. N., & Yeong, O. S. (2007). 3-(4'-Hydroxyl-3',5'-dimethoxyphenyl)propionic acid, an active principle of kimchi, inhibits development of atherosclerosis in rabbits. *J Agric Food Chem*, 55(25), 10486–10492. https://doi.org/10.1021/jf072454m
- Ikeda Y, Takahashi M. 2007. Glycosyltransferases and Glycosidases: Enzyme Mechanisms. In: Compr Glycosci. [place unknown]: Elsevier; p. 115–128. https://doi.org/10.1016/B978-044451967-2/00041-6
- Islam, M. S., & Choi, H. (2009). Antidiabetic Effect of Korean Traditional Baechu (Chinese Cabbage) Kimchi in a Type 2 Diabetes Model of Rats. J Med Food, 12(2), 292–297. https://doi.org/10.1089/jmf.2008.0181
- Jain, K. S., Kathiravan, M. K., Somani, R. S., & Shishoo, C. J. (2007). The biology and chemistry of hyperlipidemia. *Bioorganic Med Chem*, 15(14), 4674–4699. https://doi.org/10.1016/j.bmc.2007.04.031
- Jeon, S.-M. (2016). Regulation and function of AMPK in physiology and diseases. *Exp Mol Med*, 48(7), e245–e245. https://doi.org/10.1038/emm. 2016.81

Johnston, C. S., Kim, C. M., & Buller, A. J. (2004). Vinegar Improves Insulin Sensitivity to a High-Carbohydrate Meal in Subjects With Insulin Resistance or Type 2 Diabetes. *Diabetes Care, 27*(1), 281–282. https://doi.org/10.2337/ diacare.27.1.281

Joung, H., Kim, B., Park, H., Lee, K., Kim, H. H., Sim, H. C., Do, H. J., Hyun, C. K., & Do, M. S. (2017). Fermented Moringa oleifera Decreases Hepatic Adiposity and Ameliorates Glucose Intolerance in High-Fat Diet-Induced Obese Mice. J Med Food, 20(5), 439–447. https://doi.org/10.1089/jmf.2016.3860

K R R, Gopi S, Balakrishnan P. 2022. Introduction to Flavor and Fragrance in Food Processing. In: [place unknown]; p. 1–19. https://doi.org/10.1021/ bk-2022-1433.ch001

Kawada, T., Hagihara, K.-I., & Iwai, K. (1986). Effects of Capsaicin on Lipid Metabolism in Rats Fed a High Fat Diet. J Nutr, 116(7), 1272–1278. https://doi.org/10.1093/jn/116.7.1272

Kazimierczak R, Hallmann E, Lipowski J, Drela N, Kowalik A, Püssa T, Matt D, Luik A, Gozdowskif D, Rembiałkowska E. 2014. Beetroot (Beta vulgaris L.) and naturally fermented beetroot juices from organic and conventional production: Metabolomics, antioxidant levels and anticancer activity. J Sci Food Agric. 94(13):2618–2629. https://doi.org/10.1002/ jsfa.6722

Kesika, P., Sivamaruthi, B. S., & Chaiyasut, C. (2022). Health promoting effects of fermented foods against cancer: An updated concise review. *Food Sci Technol.*, 42, 1–9. https://doi.org/10.1590/fst.18220

Kim, H. J., Noh, J. S., & Song, Y. O. (2018). Beneficial effects of kimchi, a Korean fermented vegetable food, on pathophysiological factors related to atherosclerosis. J Med Food, 21(2), 127–135. https://doi.org/10.1089/jmf. 2017.3946

Kim, M. J., Lim, T., Kim, J., Ji, G. E., Lee, H., Lee, K., Kim, R. H., & Hwang, K. T. (2022). γ-Aminobutyric acid and oxalic acid contents and angiotensinconverting enzyme inhibitory activity of spinach juices cofermented with Levilactobacillus brevis GABA100 and other lactic acid bacteria. *Int J Food Sci Technol*, *57*(10), 6722–6729. https://doi.org/10.1111/ijfs. 16030

Lee, S.-Y., Park, S.-L., Hwang, J.-T., Yi, S.-H., Nam, Y.-D., & Lim, S.-I. (2012). Antidiabetic Effect of Morinda citrifolia (Noni) Fermented by Cheonggukjang in KK-A y Diabetic Mice. *Evidence-Based Complement Altern Med*, 2012, 1–8. https://doi.org/10.1155/2012/163280

Li, C., Ding, Q., Nie, S. P., Zhang, Y. S., Xiong, T., & Xie, M. Y. (2014). Carrot juice fermented with lactobacillus plantarum NCU116 ameliorates type 2 diabetes in rats. *J Agric Food Chem*, *62*(49), 11884–11891. https://doi.org/ 10.1021/jf503681r

Li, K. J., Burton-Pimentel, K. J., Vergères, G., Feskens, E. J. M., & Brouwer-Brolsma, E. M. (2022a). Fermented foods and cardiometabolic health: Definitions, current evidence, and future perspectives. *Front Nutr, 9*(September), 1–14. https://doi.org/10.3389/fnut.2022.976020

Li, R., Luo, W., Liu, Y., Chen, C., Chen, S., Yang, J., Wu, P., Lv, X., Liu, Z., Ni, L., & Han, J. (2022c). The investigation on the characteristic metabolites of Lactobacillus plantarum RLL68 during fermentation of beverage from by-products of black tea manufacture. *Curr Res Food Sci, 5*, 1320–1329. https://doi.org/10.1016/j.crfs.2022.07.014

Li M, Bao X, Zhang X, Ren H, Cai S, Hu X, Yi J. 2022b. Exploring the phytochemicals and inhibitory effects against α-glucosidase and dipeptidyl peptidase-IV in Chinese pickled chili pepper: Insights into mechanisms by molecular docking analysis. LWT. 162:113467. https://doi.org/10. 1016/j.lwt.2022.113467

Lu, B., Ren, Y., Zhang, Y., & Gong, J. (2009). Effects of genetic variability, parts and seasons on the sterol content and composition in bamboo shoots. *Food Chem*, *112*(4), 1016–1021. https://doi.org/10.1016/j.foodchem.2008. 06.059

Lu, Y., Zhang, C., Zhao, H., Min, W., Zhu, H., Wang, H., Lu, H., Li, X., Xu, Y., & Li, W. (2022). Effect of Environmental Microorganisms on Fermentation Microbial Community of Sauce-Flavor baijiu. *Foods, 12*(1), 10. https://doi.org/10. 3390/foods12010010

Maniglia BC, Rebelatto EA, Andrade KS, Zielinski A, de Andrade CJ. 2021. Polyphenols. In: Food Bioact Heal. Cham: Springer International Publishing; p. 1–39. https://doi.org/10.1007/978-3-030-57469-7\_1

Marco, M. L., Heeney, D., Binda, S., Cifelli, C. J., Cotter, P. D., Foligné, B., Gänzle, M., Kort, R., Pasin, G., Pihlanto, A., et al. (2017). Health benefits of fermented foods: Microbiota and beyond. *Curr Opin Biotechnol*, 44, 94–102. https:// doi.org/10.1016/j.copbio.2016.11.010 Marco ML, Sanders ME, Gänzle M. 2021. The International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on fermented foods. Nat Rev Gastroenterol Hepatol. 18(March). https://doi.org/10.1038/ s41575-020-00390-5

Martinez-Villaluenga, C., Peñas, E., Sidro, B., Ullate, M., Frias, J., & Vidal-Valverde, C. (2012). White cabbage fermentation improves ascorbigen content, antioxidant and nitric oxide production inhibitory activity in LPS-induced macrophages. *Lwt*, 46(1), 77–83. https://doi.org/10.1016/j.lwt.2011.10.023

Maryati Y, Susilowati A, Aspiyanto. 2020. Development of fermented vegetables in their ability to inhibit pancreatic lipase as antidyslipidemic agent. IOP Conf Ser Mater Sci Eng. 722(1). https://doi.org/10.1088/1757-899X/ 722/1/012074

Moslehi-Jenabian, S., Pedersen, L. L., & Jespersen, L. (2010). Beneficial effects of probiotic and food borne yeasts on human health. *Nutrients, 2*(4), 449–473. https://doi.org/10.3390/nu2040449

Pang, X.-N., Han, B.-Z., Huang, X.-N., Zhang, X., Hou, L.-F., Cao, M., Gao, L.-J., Hu, G.-H., & Chen, J.-Y. (2018). Effect of the environment microbiota on the flavour of light-flavour Baijiu during spontaneous fermentation. *Sci*, 8(1), 3396. https://doi.org/10.1038/s41598-018-21814-y

Park, K. Y., Jeong, J. K., Lee, Y. E., & Daily, J. W. (2014). Health benefits of kimchi (korean fermented vegetables) as a probiotic food. *J Med Food*, *17*(1), 6–20. https://doi.org/10.1089/jmf.2013.3083

Park, H. S., Kim, W. K., Kim, H. P., & Yoon, Y. G. (2015). The Efficacy of Lowering Blood Glucose Levels Using the Extracts of Fermented Bitter Melon in the Diabetic Mice. J Appl Biol Chem, 58(3), 259–265. https://doi.org/10.3839/ jabc.2015.041

Pisoschi, A. M., & Pop, A. (2015). The role of antioxidants in the chemistry of oxidative stress: A review. *Eur J Med Chem*, *97*, 55–74. https://doi.org/10. 1016/j.ejmech.2015.04.040

Puska, P. (2002). Nutrition and global prevention on non-communicable diseases. *Asia Pacific J Clin Nutr, 11*(SUPPL. 8), S755–S758. https://doi.org/10.1046/j.1440-6047.11.s.5.x

Rajendran, S., Silcock, P., & Bremer, P. (2023). Flavour Volatiles of Fermented Vegetable and Fruit Substrates: A Review. *Molecules*, 28(7), 3236. https:// doi.org/10.3390/molecules28073236

Ray RC, Joshi VK. 2014. Fermented foods: Past, present and future. In: Ray RC, Didier M, editors. Microorg Ferment Tradit Foods. [place unknown]: CRC Press; p. 1–36. https://doi.org/10.1201/b17307

Reuter, S., Gupta, S. C., Chaturvedi, M. M., & Aggarwal, B. B. (2010). Oxidative stress, inflammation, and cancer: How are they linked? *Free Radic Biol Med*, 49(11), 1603–1616. https://doi.org/10.1016/j.freeradbiomed.2010.09.006

Salamone, D., Rivellese, A. A., & Vetrani, C. (2021). The relationship between gut microbiota, short-chain fatty acids and type 2 diabetes mellitus: The possible role of dietary fibre. *Acta Diabetol, 58*(9), 1131–1138. https://doi. org/10.1007/s00592-021-01727-5

Saldera KA, Ali S, Ashfaq A. 2017. ATHEROSCLEROSIS; Prof Med J. 24(10):1550– 1555. https://doi.org/10.29309/TPMJ/2017.24.10.717

Singer M. 2014. Non-Communicable Diseases. In: Wiley Blackwell Encycl Heal Illness, Behav Soc. Chichester, UK: John Wiley & Sons, Ltd; p. 1686–1690. https://doi.org/10.1002/9781118410868.wbehibs407

Singhal P, Satya S, Naik SN. 2021. Fermented bamboo shoots: A complete nutritional, anti-nutritional and antioxidant profile of the sustainable and functional food to food security. Food Chem Mol Sci. 3(September):100041. https://doi.org/10.1016/j.fochms.2021.100041

Sivamaruthi, B., Kesika, P., Prasanth, M., & Chaiyasut, C. (2018). A Mini Review on Antidiabetic Properties of Fermented Foods. *Nutrients*, *10*(12), 1973. https://doi.org/10.3390/nu10121973

Skowron K, Budzyńska A, Grudlewska-Buda K, Wiktorczyk-Kapischke N, Andrzejewska M, Wałecka-Zacharska E, Gospodarek-Komkowska E. 2022. Two Faces of Fermented Foods—The Benefits and Threats of Its Consumption. Front Microbiol. 13. https://doi.org/10.3389/fmicb.2022.845166

Spano, G., Russo, P., Lonvaud-Funel, A., Lucas, P., Alexandre, H., Grandvalet, C., Coton, E., Coton, M., Barnavon, L., Bach, B., et al. (2010). Biogenic amines in fermented foods. *Eur J Clin Nutr, 64*(S3), S95–S100. https://doi.org/10. 1038/ejcn.2010.218

Sun, W., Shahrajabian, M. H., & Lin, M. (2022). Research Progress of Fermented Functional Foods and Protein Factory-Microbial Fermentation Technology. *Fermentation*, 8(12), 688. https://doi.org/10.3390/fermentation8120688

Tahir, Z., Saeed, F., Nosheen, F., Ahmed, A., & Anjum, F. M. (2022). Comparative study of nutritional properties and antioxidant activity of raw and fermented (black) garlic. *Int J Food Prop, 25*(1), 116–127. https://doi.org/10. 1080/10942912.2022.2026954

- Terefe NS. 2016. Emerging Trends and Opportunities in Food Fermentation. [place unknown]: Elsevier. https://doi.org/10.1016/b978-0-08-100596-5. 21087-1
- Tyagi, S., Sharma, S., Gupta, P., Saini, A., & Kaushal, C. (2011). The peroxisome proliferator-activated receptor: A family of nuclear receptors role in various diseases. J Adv Pharm Technol Res, 2(4), 236. https://doi.org/10.4103/ 2231-4040.90879
- Uuh-Narvaez JJ, Segura-Campos MR. 2021. Cabbage (Brassica oleracea var. capitata): A food with functional properties aimed to type 2 diabetes prevention and management. J Food Sci. 86(11):4775–4798. https://doi. org/10.1111/1750-3841.15939
- Varzakas T, Zakynthinos G, Proestos C, Radwanska M. 2017. Fermented Vegetables. In: Minim Process Refrig Fruits Veg [Internet]. [place unknown]; p. 537–584. https://doi.org/10.1007/978-1-4939-7018-6\_15
- Verardo, V., Gómez-Caravaca, A., & Tabanelli, G. (2020). Bioactive Components in Fermented Foods and Food By-Products. *Foods*, 9(2), 153. https://doi. org/10.3390/foods9020153
- Verni M, Verardo V, Rizzello CG.2019. How Fermentation Affects the Antioxidant Properties of Cereals and Legumes. Foods. 2019 Aug 24;8(9):362. 10.3390/foods8090362.
- Wacher C, Díaz-Ruiz G, Tamang JP. 2010. Fermented Vegetable Products. In: Fermented Foods and Beverages of the World. [place unknown]: CRC Press; p. 149–190. https://doi.org/10.1201/EBK1420094954-9
- Wang, Z., Hwang, S. H., Lee, S. Y., & Lim, S. S. (2016). Fermentation of purple Jerusalem artichoke extract to improve the α-glucosidase inhibitory effect in vitro and ameliorate blood glucose in db/db mice. *Nutr Res Pract*, 10(3), 282. https://doi.org/10.4162/nrp.2016.10.3.282
- Wu SC, Su YS, Cheng HY. 2011. Antioxidant properties of Lactobacillus-fermented and non-fermented Graptopetalum paraguayense E. Walther at different stages of maturity. Food Chem. 129(3):804–809. https://doi.org/ 10.1016/j.foodchem.2011.05.025
- Yeo SK, Ewe JA. 2015. Effect of fermentation on the phytochemical contents and antioxidant properties of plant foods. [place unknown]: Elsevier Ltd. https://doi.org/10.1016/B978-1-78242-015-6.00005-0
- Yeon, S. J., Kim, J. H., Cho, W. Y., Kim, S. K., Seo, H. G., & Lee, C. H. (2019). In vitro studies of fermented Korean Chung-Yang hot pepper phenolics as inhibitors of key enzymes relevant to hypertension and diabetes. *Foods.*, 8(10), 498. https://doi.org/10.3390/foods8100498
- Zhu G, Fang Q, Zhu F, Huang D, Yang C. 2021. Structure and Function of Pancreatic Lipase-Related Protein 2 and Its Relationship With Pathological States. Front Genet. 12. https://doi.org/10.3389/fgene.2021.693538

# **Publisher's Note**

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

# Ready to submit your research? Choose BMC and benefit from:

- fast, convenient online submission
- thorough peer review by experienced researchers in your field
- rapid publication on acceptance
- support for research data, including large and complex data types
- gold Open Access which fosters wider collaboration and increased citations
- maximum visibility for your research: over 100M website views per year

#### At BMC, research is always in progress.

Learn more biomedcentral.com/submissions

