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REVIEW

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Bioactive properties and therapeutic aspects of fermented vegetables: a review

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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

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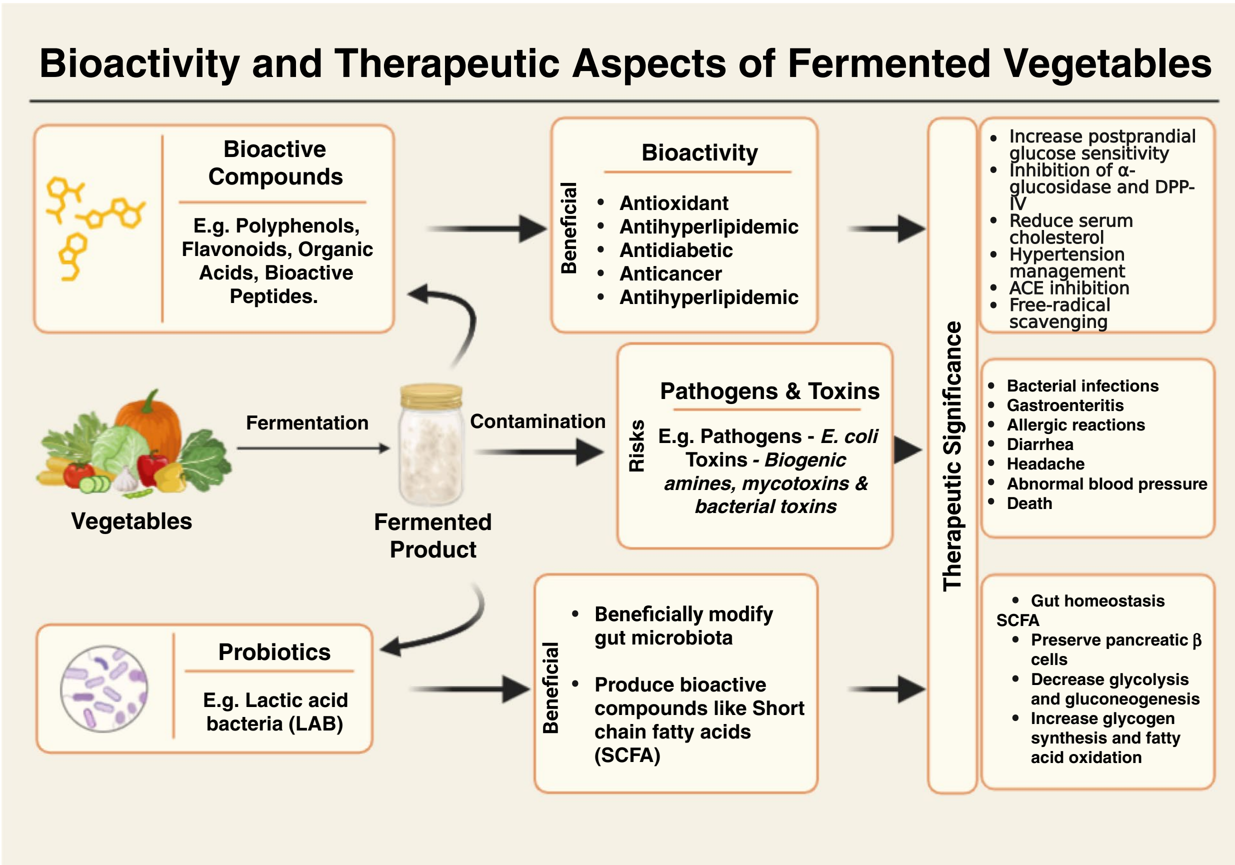
Graphical Abstract



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

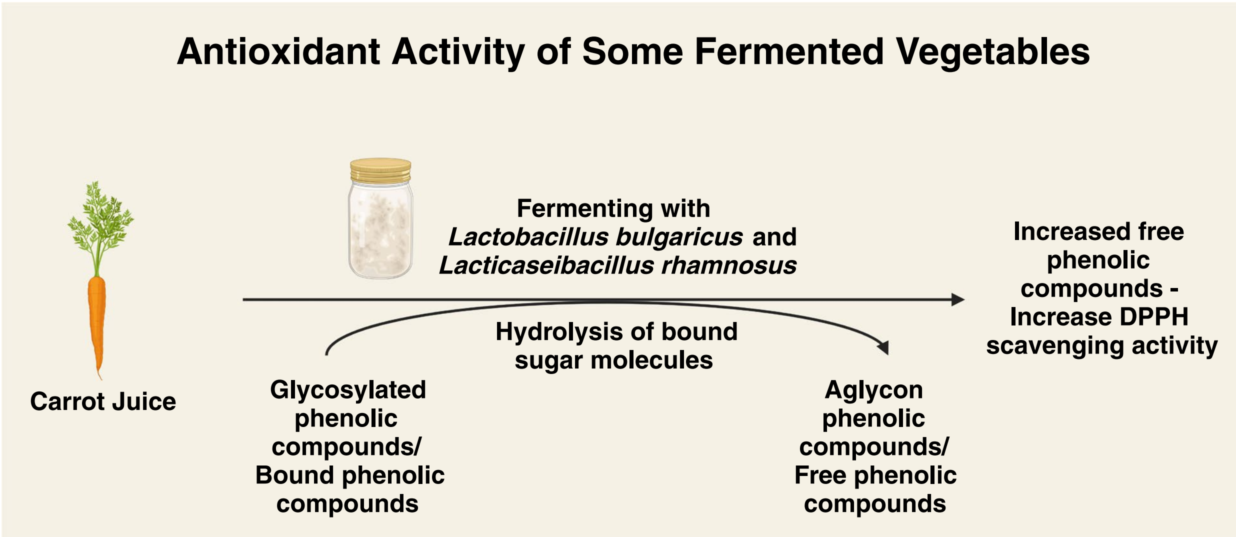


Fig. 1 Antioxidant activity of some fermented vegetables

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

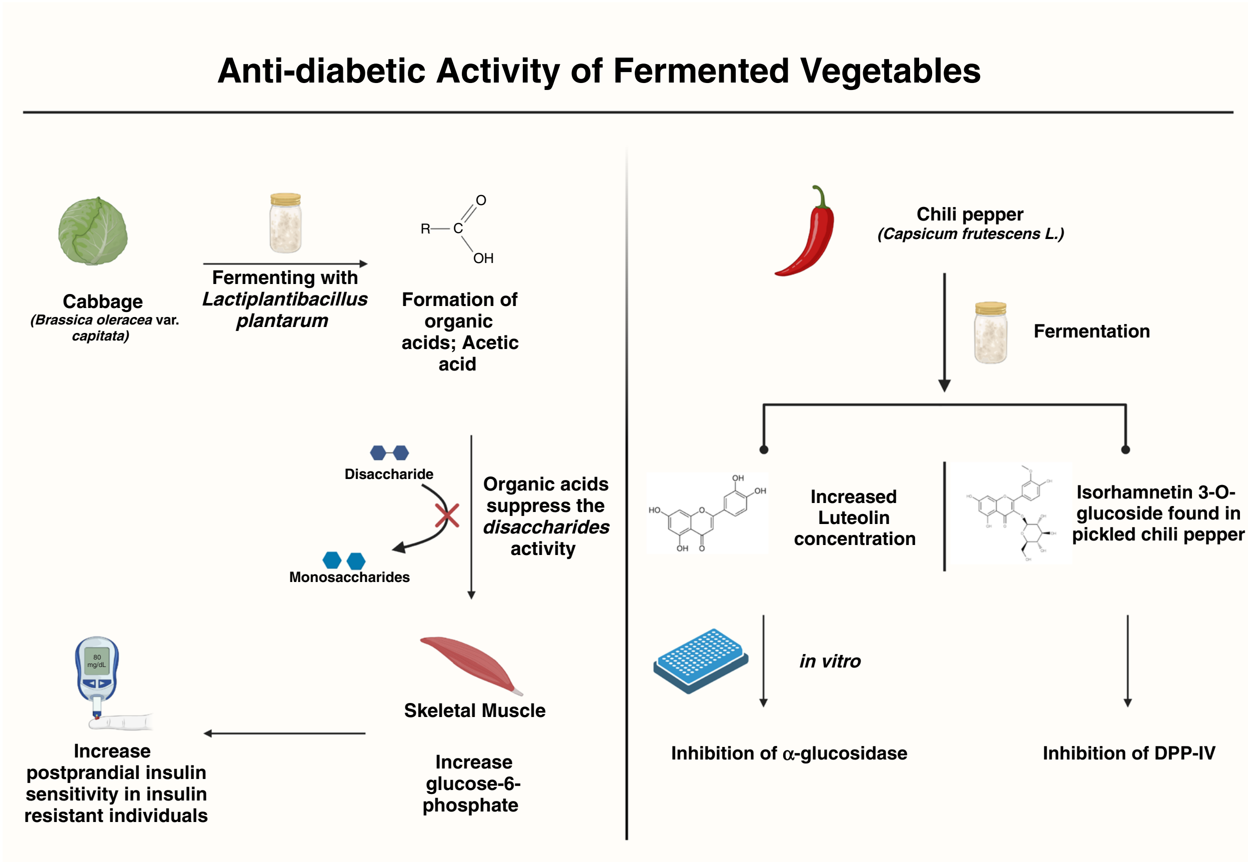


Fig. 2 Anti-diabetic activity of fermented vegetables

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 anti-inflammatory, 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

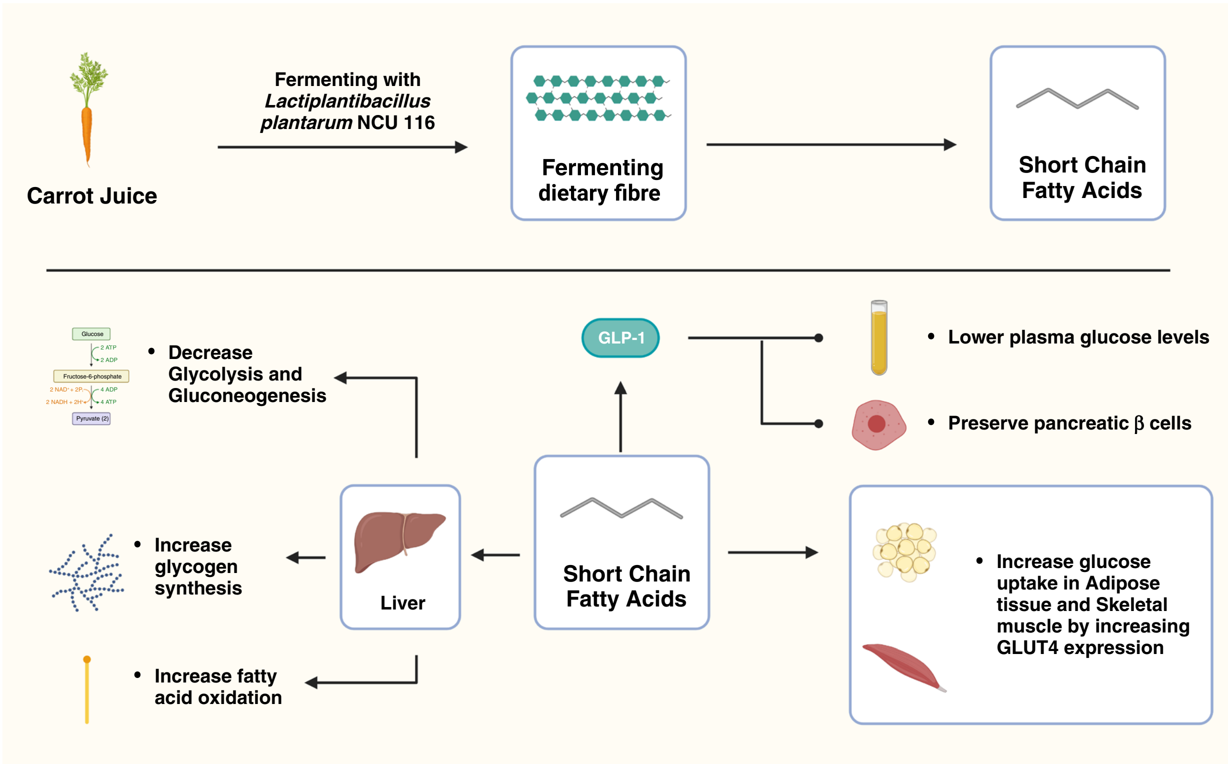


Fig. 3 Anti-diabetic activity of SCFA produced during vegetable fermentation

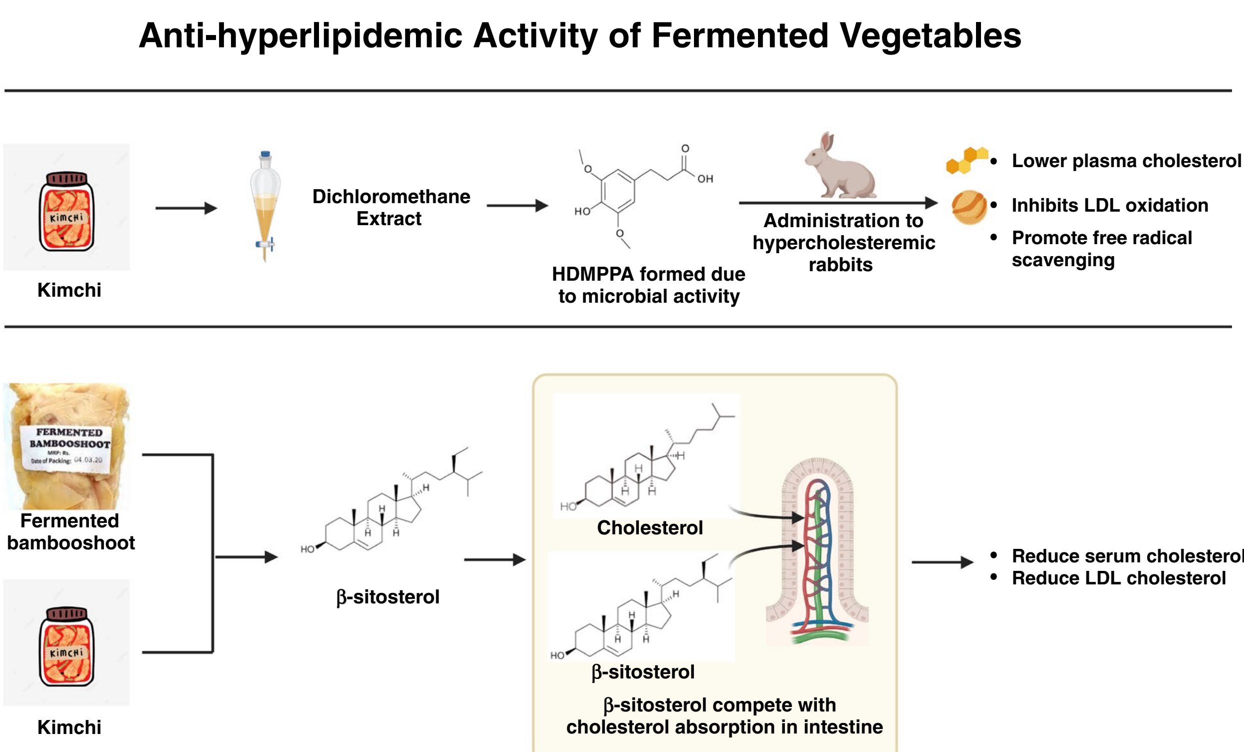


Fig. 4 Anti-hyperlipidemic activity of fermented vegetables

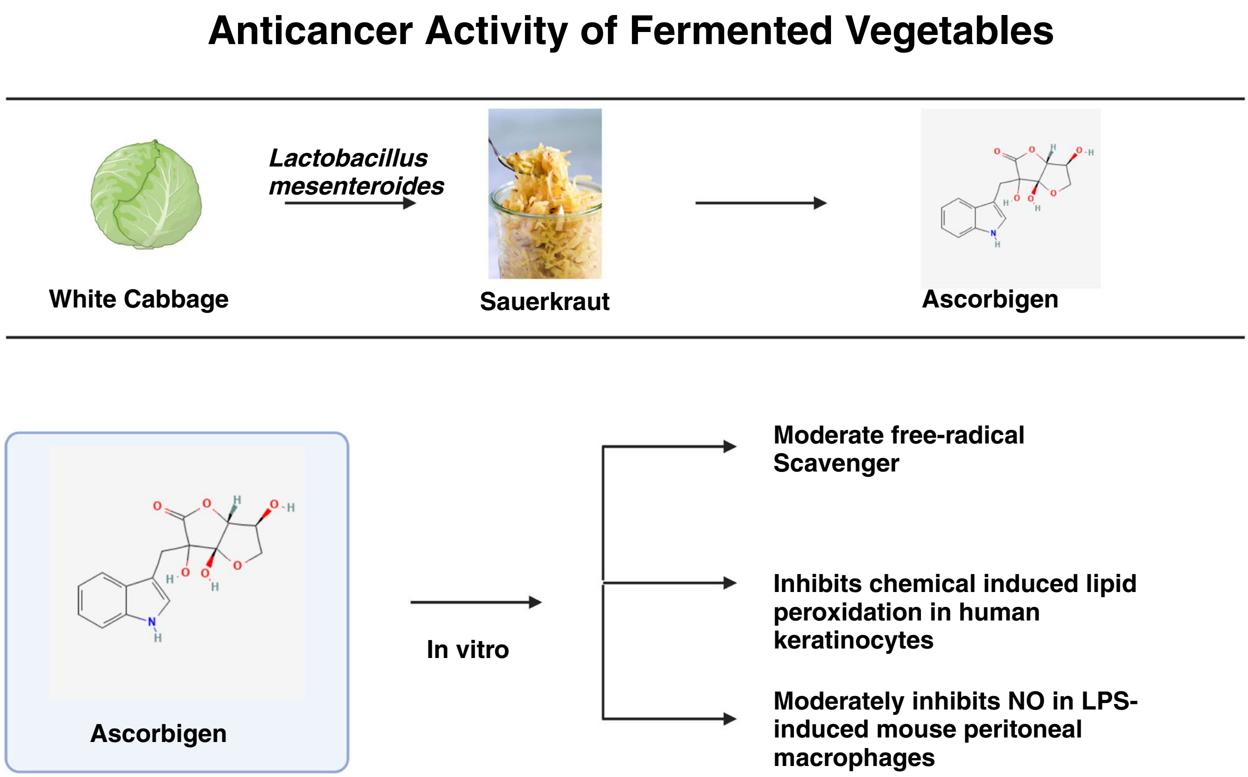


Fig. 5 Anticancer activity of fermented vegetables

(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 μmol TE/g compared to the fresh shoots, which were 1.72 μmol 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,

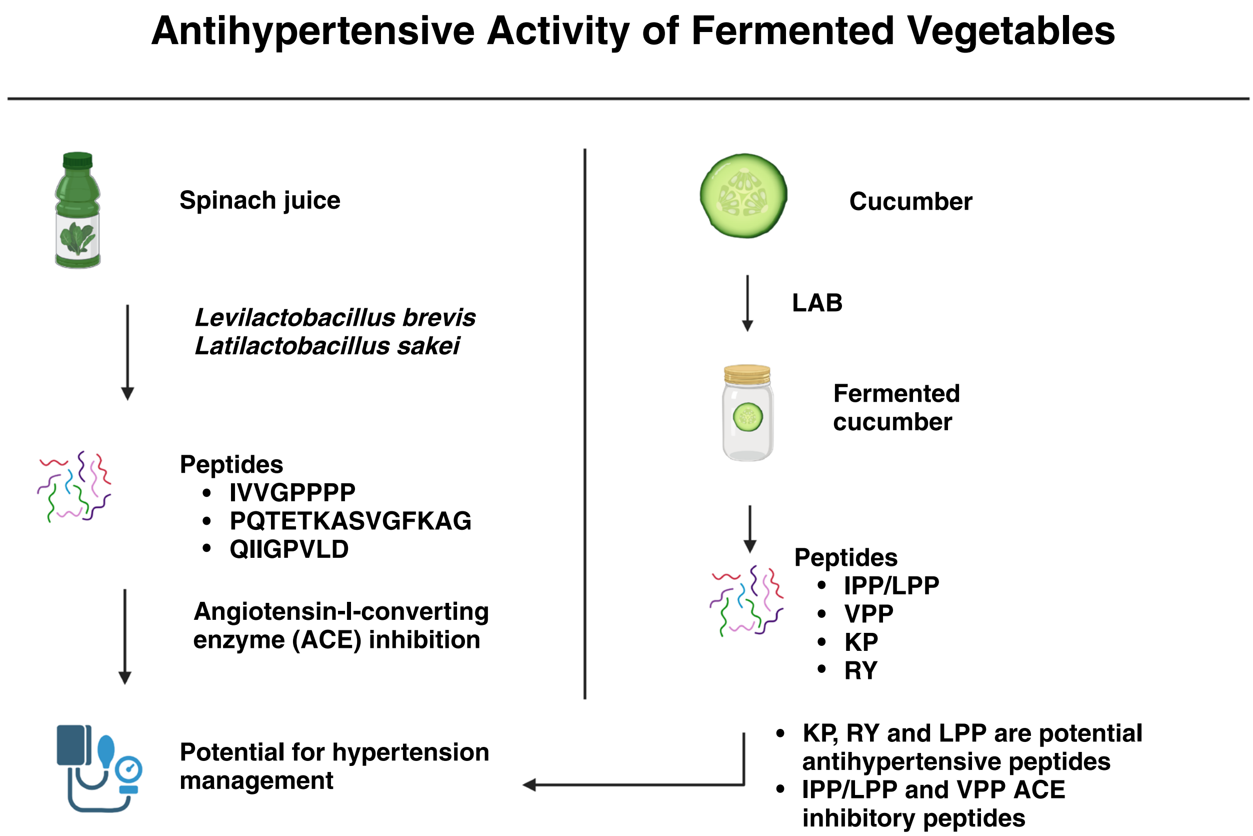


Fig. 6 Antihypertensive activity of fermented vegetables

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 β-cells. The low AOX in the pancreas increases its susceptibility to oxidative stress resulting in β-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 α-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 α-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 short-chain 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 α-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

Table 1 Summary of bioactivity and mechanism of action

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

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'-azino-bis(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-I- 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 non-saponifiable 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 β-sitosterol and campesterol, are commonly found in plant-based foods and have been associated with various health benefits, including their cholesterol-lowering 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 β-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). β-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 non-fermented *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 vegetable-based 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 mesenteroides* 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 ^{3}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 β-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 high-quality 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.

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