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Article

Exploration of fermentation methods in enhancing bioactive compounds in green plants: a review

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Abstract

Green plants are recognized for their potent free radical inhibition, attributed to their bioactive compounds, such as phenolics, which neutralize free radicals by donating hydrogen atoms or electrons. Though present in small quantities, these bioactive compounds offer significant health benefits, including managing immune disorders, cardiovascular diseases, diabetes, and neurodegenerative conditions. Previous methods to enhance these compounds, such as physical processing, microencapsulation, genetic engineering, and solvent extraction, have limitations. Fermentation has emerged as an eco-friendly and effective alternative for increasing bioactive compound levels in green plants. This process involves the hydrolysis of phenolic fucosides by β-glucosidase, releasing free phenolics and enhancing bioactivity. This review focuses on some of the types of microorganisms that can be involved, as well as the types of green plants that have the potential to be enhanced with bioactive compounds.

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1. Introduction

Bioactive compounds are chemical components contained in plants and other organisms that have biological effects on living things. They act as essential nutrients and provide additional health benefits (1). These compounds can interact with biological systems and affect various physiological functions, including antioxidant, anti-inflammatory, antimicrobial, as well as anticancer activity (2). Various studies have shown that regular consumption of bioactive compounds can reduce the risk of chronic diseases such as cancer, heart disease and diabetes (8).

Bioactive compounds commonly found in green plants include polyphenols, flavonoids, carotenoids, and alkaloids (3). Polyphenols, for example, have strong antioxidant properties protect cells from oxidative damage, can lower blood pressure, and improve blood vessel function (4). Flavonoids, which are widely found in green tea leaves, are known to have anti-inflammatory and cardioprotective effects (5). Carotenoids, such as beta-carotene, have an important role in eye health and boosting the immune system (6). Alkaloids, which are found in various plants such as coffee and chocolate, have a stimulating effect and may affect nervous system function (7).

Bioactive compounds also have an important role in the development of functional food products, which are designed to provide health benefits in addition to basic nutrition (11). These products can be part of a broader disease prevention strategy and contribute to improved quality of life. Despite their importance, bioactive compounds are often found in relatively small amounts in plants (12). Attempts to increase the concentration of bioactive compounds using conventional methods, such as chemical solvent extraction, have limitations. For example, these method risks leaving chemical residues and damaging the bioactive compound components (13). Conventional methods are also often ineffective in

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breaking down complex matrices in plants that harbor bioactive compounds, resulting in low bioavailability of these compounds (14). This poses a challenge in efforts to increase the amount and quality of bioactive compounds that can be absorbed by the human body. One method that can be employed is fermentation, which utilizes various microorganisms.

Fermentation is a metabolic process that converts organic compounds, especially carbohydrates, into simpler products such as alcohol, acids, and gases with the help of microorganisms such as bacteria, yeast, and fungi (15). This process has long been used in the production of food and beverages, such as yogurt, cheese, and tempeh, which not only increases the durability of food but also its nutritional value (16). In the context of enhancing bioactive compounds, fermentation offers significant potential. Microorganisms involved in fermentation are able to break down complex plant components, such as cellulose fibers, into simpler, easily absorbed compounds (17). In addition, some microorganisms can synthesize new bioactive compounds (18) or enhance the activity of existing ones through biotransformation (19). For example, fermentation with lactic acid bacteria can increase the concentration of polyphenols in green plants (20), while fermentation with certain fungi can increase the content of alkaloids (21).

Fermentation processes also tend to be more environmentally friendly and economical compared to conventional methods (22). In addition, fermentation can be carried out using simple technology that can be adopted at various scales, ranging from household scale to large industries (23). Thus, fermentation not only provides an opportunity to increase the content of bioactive compounds in green plants but also paves the way for innovation in the development of functional food products that are richer in health benefits.

2. Materials and Methods

The search for articles was performed using the Google Scholar and Scopus electronic databases until June 2025. The main keywords used were: “green plants derived bioactive components,”; “green plants fermentation,”; “health benefit of bioactive compounds,”; “anti-diabetic activity,”; “anti-cancerous attributes,” and “anti-oxidant activity,” among others. All the included references were manually selected and reviewed by the authors.

3. Results and Discussion

3.1. Bioactive Compound in Green-Plants

Bioactive compounds are natural components found in foods, especially in plants, that have biological effects on the human body or other organism (24). Although these compounds are not essential nutrients like vitamins or minerals, they have the ability to affect health positively. In green plants, bioactive compounds are generally derived from secondary metabolites, products of metabolic processes that are not directly involved in plant growth, development, or reproduction (25). Some examples of bioactive compounds commonly found in green plants include flavonoids, polyphenols, carotenoids, glucosinolates and chlorophyll. Flavonoids, which are found in vegetables such as spinach and broccoli, are best known for their powerful antioxidant properties (26). Polyphenols, found in green tea and vegetables like kale, have anti-inflammatory and antioxidant properties (27). Carotenoids such as lutein and zeaxanthin, found in green vegetables such as spinach and lettuce, play an important role in maintaining eye health (28).

Glucosinolates, found in cruciferous vegetables such as broccoli and cabbage, have potential as anticancer agents (29). Chlorophyll, a naturally occurring green compound found in all green plants, apart from giving them their green color, also has potential as a detoxifying agent in the body (30).

The health benefits of bioactive compounds are diverse. As antioxidants, compounds such as flavonoids and polyphenols protect the body's cells from free radical damage, which is important in the prevention of chronic diseases such as cancer, diabetes and heart disease (31). These compounds also have anti-inflammatory properties that can help reduce chronic inflammation, a condition associated with various degenerative diseases (32). In addition, some bioactive compounds such as glucosinolates can inhibit cancer cell growth and promote apoptosis, which makes them potentially usable as cancer prevention and therapy agents (33). Carotenoids such as lutein and zeaxanthin are essential for eye health, especially in protecting the eyes from ultraviolet light damage and preventing age-related macular degeneration (34).

In industry, bioactive compounds have wide applications. In the pharmaceutical field, compounds such as flavonoids and polyphenols are used in drug development and nutritional supplements, especially antioxidant supplements (35). In the cosmetics industry, these compounds are used in various skincare products to fight premature aging and protect the skin from free radical damage (36,37). In the food and beverage industry, bioactive compounds are added to enhance the health benefits of products, such as green tea extract, which is often added to energy drinks or healthy foods (3). Thus, bioactive compounds in green plants are not only important for human health, but also have great potential in various industrial applications. The development of methods to increase the content of these compounds, including through fermentation, could open up new opportunities in the health and industrial sectors.

3.2. Bioactive Compound Enhancement Method

In an effort to increase the content of bioactive compounds in plants, there are several methods commonly used, including non-fermentation techniques. One of the most common methods is compound extraction and isolation, where bioactive compounds are extracted from plants using a specific solvent, and then isolated to obtain the desired compounds (38). However, this method has limitations, such as the risk of compound degradation due to the use of chemical solvents and selectivity issues, where it is difficult to extract certain compounds without mixing other compounds (39).

In addition, genetic modification is also one of the approaches often used to increase the production of certain bioactive compounds in plants. Despite its effectiveness, genetic modification is often faced with ethical issues and strict regulations regarding genetically modified organisms (GMOs), as well as the risk of genetic instability that could result in plants with undesirable characteristics (40). Conventional plant breeding, which involves crossing plants to produce varieties with higher bioactive compound content, is also used, but this process is time-consuming and not always successful, especially if the desired trait is not consistently inherited (41).

3.3. Fermentation Methods and Their Effect on Bioactive Compounds

Fermentation is a biochemical process in which microorganisms such as bacteria, yeasts, or fungi convert organic matter into simpler products (15). In the context of green plants, fermentation has been recognized as a potential method to increase the content of bioactive compounds, such as polyphenols, flavonoids, and other phytochemicals (42). Microorganisms involved in fermentation can break down plant cell walls, release the bioactive compounds contained within, and even produce new, more beneficial compounds (43–45). This process not only increases the bioavailability of bioactive compounds but can also reduce anti-nutritional compounds that can inhibit nutrient absorption. For example, fermentation has been reported to reduce phytic acid and oxalate levels by 44.4 and 50.9% in three African locust bean accessions, respectively (46).

The effect of fermentation on the bioactive content of green plants depends largely on the type of microorganisms used as well as fermentation conditions such as pH, temperature and fermentation time (47). For example, fermentation with lactic acid bacteria of leafy greens such as kale and spinach has been shown to increase levels of polyphenols and antioxidants, which are important for fighting free radicals in the body(48,49). Thus, fermentation serves not only as a preservation method but also as an innovative technique to enrich the nutritional value and health benefits of greenery.

3.4. Green Plants and Their Health Benefits

Green plants in Indonesia, such as moringa, spinach, and katuk leaves, have great potential to be enhanced with bioactive compounds through fermentation methods. Indonesia, with its abundant biodiversity, has many types of green plants that are rich in bioactive compounds such as polyphenols, flavonoids, and alkaloids that have health benefits. Through fermentation, the content of bioactive compounds in these green plants can be increased, resulting in food products that are not only more nutritious, but also have the potential as basic ingredients in the pharmaceutical and health supplement industries, providing significant economic added value. The bioactive compounds and its health benefits of green plants can be seen in Table 1.

Table 1. Green plants and their bioactive compounds

Green-plants	Main Bioactive Compounds	Health Benefits	Ref.
Cabbage (*Brassica oleracea* var. *capitata*)	Phenolic acids; flavonoid; anthocyanins; glucosinolates	Anti-diabetic activity	(50)
Spinach (*Spinacia oleracea*)	Gamma-aminobutyric acid	Hypertension management	(51)
Kale (*Brassica oleracea*)	Polyphenols; sulforaphane	Antioxidant activity	(52)
Green tea leaves (*Camellia sinensis*)	Polyphenols: Catechins	Antioxidative, anti-obesity, and anti-carcinogenic	(53)
Kelor (*Moringa oleifera*)	Phenolics: flavonoids	Antioxidant activity	(54)

3.5. Microorganisms Involved

Microorganisms play a key role in the fermentation process of greenery, where they convert complex components in the plant into simpler, useful compounds. Lactic acid bacteria, yeasts, and molds are examples of commonly used microorganisms in this fermentation. The microorganisms involved and their mechanisms in enhancing bioactive compounds are presented in Table 2.

Table 2. Microorganisms and Their Role in Fermentation Process

Type of Microorganisms	Microorganisms Involved	Enhanced Bioactive Compounds	Mechanism	Ref.
Lactic Acid Bacteria (LAB)	*Lactobacillus plantarum*	Antioxidant	Increases the levels of proteins that regulate the endogenous antioxidant system and catalyze antioxidant enzymes	(49)
	Lactobacillus acidophilus	Phenolics and flavonoids	Enzymes such as beta-glucosidase can break down glycosides into aglycones that are more biologically active and have higher antioxidant activity.	(55)
	Lactococcus lactis	Isoflavone aglycones	Modifying isoflavones into aglycone forms that are more easily absorbed by the body, increasing their bioavailability	(56)
Bacteria	*Acetobacter pasteurianus*	Organic acids; polyphenols	Produce a variety of secondary metabolites, including other organic acids and antioxidant compounds, which may contribute to the enhanced biological activity of the final product	(57)
Yeast	*Saccharomyces cerevisiae*	Vitamins; glutathione	Synthesize various vitamins such as B vitamins, as well as other bioactive compounds such as glutathione, which is a powerful antioxidant.	(58)
	Aspergillus oryzae	Phenolics	The high variety of enzymes produced can release compounds previously bound to the cell wall.	(59)
	Rhizopus oryzae	Phenolics	The resulting enzymes weaken the ether bonds between bound phenolics and structural components, or release bound phenolic compounds through hydrolysis.	(13)

3.6. Advantages and Disadvantages

Fermentation offers a number of advantages in increasing the content of bioactive compounds in green plants. One of these advantages is the ability of fermentation to increase the bioavailability of bioactive compounds such as polyphenols, flavonoids, and antioxidants. Microorganisms involved in fermentation can break down plant cell walls, releasing and converting bioactive compounds into forms that are more easily absorbed by the body (17,43,45). In addition, fermentation can also reduce anti-nutritional compounds that can inhibit nutrient absorption, making greenery more nutritious (46).

However, fermentation methods also have some disadvantages to consider. One disadvantage is the dependence on very specific fermentation conditions, such as temperature, pH, and the type of microorganisms used (47). If these conditions are not right, fermentation can produce unwanted products or even destroy existing bioactive compounds (60,61). In addition, fermentation takes a longer time compared to other processing methods, which can be challenging in large-scale production (62). The risk of contamination by pathogenic microorganisms also needs to be watched out for, as it can result in products that are unsafe for consumption (63). While fermentation has great potential, it is important to understand and manage these risks to maximize its benefits.

3.7. Challenges and limitation

There are several important obstacles to overcome when using fermentation techniques to increase bioactive chemicals in green plants. The requirement for strict control over fermentation conditions, including temperature, pH, and the kind of microorganisms utilized, is one of the major obstacles. Small changes in these parameters might have a significant impact on the fermentation process, leading to inconsistent or even decreased production of bioactive chemicals. Furthermore, because not all microbes can increase a certain bioactive chemical, attention must be taken while choosing the microorganisms to use in fermentation.

The possibility of pathogenic microbe infection during the fermentation process is another drawback. This contamination can lead to items that are dangerous to eat if it is not properly controlled. Furthermore, compared to other processing techniques, fermentation typically takes longer, which poses a challenge for large-scale production. There are also gaps in our understanding of the knowledge and investigation needed to completely comprehend the ways in which various fermentation condition and microorganisms influence the bioactive chemicals found in various kind of green plants. Because of these difficulties, fermentation is a complicated process that requires careful application.

4. Conclusions

In the context of Indonesian food processing, fermentation is a promising technique to boost the amount of bioactive chemicals in green plants. This procedure makes use of microbes that may decompose plant materials and boost the bioavailability of substances that are beneficial to health, like flavonoids and polyphenols. These microorganisms include yeast, lactic acid bacteria, and certain types of fungi. For instance, by fermenting with lactic acid bacteria, moringa and spinach leaves might have higher antioxidant and flavonoid content. Fermentation has many advantages, but it also has disadvantages, such as the requirement for careful control over fermentation conditions and the possibility of contamination. But because of Indonesia's rich biodiversity, there is a great chance to investigate fermentation techniques further as a novel approach to improve the nutritional content and health benefits of local green plants like cassava and katuk leaves, while also creating the possibility of producing more valuable food and health products.

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Conflicts of Interest

The author declares no conflict of interest.

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