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Edamame (Glycine max L.) as a Functional Food: Integrating Nutritional Composition, Phytochemicals, and Health Implications—A Comprehensive Review”

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Abstract

Edamame (*Glycine max* L.), sometimes referred to as vegetable soybean, has drawn more and more attention as a functional food that is high in nutrients and has important health benefits. This thorough analysis summarizes the most recent research on the phytochemical profile, nutritional makeup, and possible health effects of edamame intake. Edamame is an important part of plant-based diets since it is rich in high-quality protein, dietary fiber, vital fatty acids, vitamins, and minerals. Its nutraceutical potential is further enhanced by the presence of bioactive substances such isoflavones, saponins, phenolic acids, and antioxidants. Regular edamame consumption has been linked to enhanced cardiovascular health, glycemic management, anti-inflammatory benefits, and maybe anticancer characteristics, according to recent research. Additionally, the analysis looks at how processing and storage conditions affect nutrient retention and bioavailability. Also, given that edamame has a smaller environmental impact than animal-based protein sources, its place in sustainable food systems is examined.

The need for more research to develop consistent dietary recommendations is highlighted by the limits in clinical data and the heterogeneity in study techniques, despite encouraging results. All things considered, edamame shows promise as a functional food with several advantages for sustainable nutrition and human health.

Keywords:- Edamame, *Glycine max*, Functional food, Phytochemicals, Isoflavones, Antioxidants and Plant-based protein.

Introduction

The green, immature edamame pods are picked at the R6 development stage, prior to the soybean plant reaching full maturity. For generations, edamame has been used as a vegetable and snack in East Asian nations, especially China and Japan. Due to its tasty flavor, plenty of nutrients, and compatibility with contemporary dietary habits, its popularity has grown around the world in recent decades (Shurtleff & Aoyagi, 2016; Mimura *et al*., 2017). Edamame has a different taste and nutritional profile than fully developed soybeans since it is eaten fresh or with little processing (Johnson *et al*., 1999).

Edamame's composition, texture, and use are very different from those of mature soybeans. Edamame is eaten as a whole vegetable, but mature soybeans are usually processed into products like oil, flour, and protein isolates. Compared to mature soybeans, edamame has a greater moisture content, less anti-nutritional elements, and a sweeter flavor (Mebrahtu *et al*., 2004; Rao & Bhagsari, 2007). Furthermore, edamame is more palatable and has a softer texture during the juvenile stage of harvesting, which makes it more suitable for direct human ingestion (Xu *et al*., 2015). Interest in edamame has increased because to the growing need for functional meals worldwide. Foods that offer health advantages beyond basic nutrition, such as preventing chronic illnesses and promoting general well-being, are referred to as functional foods (Granato *et al*., 2020; Martirosyan & Singh, 2015). Customers are looking for nutrient-dense, plant-based substitutes as a result of growing awareness of lifestyle-related conditions including obesity, diabetes, and cardiovascular disease (Siro *et al*., 2008). Because of its abundance of high-quality protein, dietary fiber, essential fatty acids, vitamins, and minerals, edamame has become a potential functional food in this regard (Messina, 2016).

Additionally, edamame is a good source of bioactive substances, especially isoflavones like daidzein and genistein, which have been linked to hormone-modulating, anti-inflammatory, and antioxidant properties (Kumar *et al*., 2010; Zaheer & Akhtar, 2017). These phytochemicals support edamame's possible health advantages, which include better cardiovascular health, better glycemic management, and a lower risk of several types of cancer (Rizzo & Baroni, 2018; Taku *et al*., 2011). The significance of soybean-based foods like edamame, which have a less environmental impact than animal-derived protein sources, has been further underlined by the growing trend toward plant-based diets and sustainable food systems (Clark & Tilman, 2017). Edamame is a significant part of contemporary functional diets because of its special blend of nutritional value, bioactive substances, and health-promoting qualities. In order to provide a thorough understanding of edamame's role as a functional meal, this study attempts to incorporate current research on the nutritional content, phytochemical profile, and health implications of edamame.

Nutritional Composition Of Edamame

- **Macronutrients**

The complex macronutrient composition of edamame, especially its high-quality protein content, is well-known. Edamame offers a complete protein with all the necessary amino acids needed for human nutrition, in contrast to many plant-based alternatives (Rutherfurd *et al*., 2015). Edamame is a useful substitute in vegetarian and vegan diets since the protein digestibility and amino acid score of soybean-derived products are similar to those of animal proteins (Hughes *et al*., 2011).

- Beneficial lipids, mostly unsaturated fatty acids like linoleic and alpha-linolenic acids, are present in edamame in addition to protein. By lowering low-density lipoprotein (LDL) cholesterol levels, these good fats are essential for preserving cardiovascular health (Fehr & Caviness, 1977; Sacks et al., 2006). Edamame's nutritional value is further enhanced by the lipid fraction's comparatively low content of saturated fats. Edamame has a substantial quantity of dietary fiber in addition to modest levels of carbohydrates. Glycemic management, satiety, and digestive health are all enhanced by this fiber (Slavin, 2013). According to Mudryj et al. (2014), the presence of both soluble and insoluble fiber promotes gut microbiota and lowers the risk of metabolic diseases.

- **Micronutrients**

Essential micronutrients, such as vitamins and minerals required for a variety of physiological processes, are also abundant in edamame. Vitamins including folate (vitamin B9), vitamin K, vitamin C, and provitamin A carotenoids are very abundant in it. While vitamin K is necessary for blood clotting and bone metabolism, folate is crucial for DNA synthesis and cell division (McGee, 2004; USDA, 2019).

- Iron, calcium, magnesium, and potassium are among the important minerals that edamame offers in substantial quantities. According to Weaver et al. (2013), these minerals support processes including oxygen delivery, bone health, enzyme reactions, and electrolyte balance. When appropriately processed, the bioavailability of these micronutrients is still reasonably high when compared to other legumes, despite the effect of some anti-nutritional factors (Gupta et al., 2015).

- **Comparison with Other Legumes**

Edamame has clear nutritional advantages over other popular legumes including lentils, chickpeas, and mature soybeans. Edamame is more suited for direct ingestion because to its higher moisture content, lower amounts of anti-nutritional chemicals, and superior palatability than mature soybeans, which typically have higher total protein and fat content (Messina, 1999). Compared to chickpeas and lentils, edamame includes improved protein quality and a more beneficial fatty acid profile, including greater amounts of polyunsaturated fats (Jukanti *et al*., 2012). Furthermore, edamame offers a wider range of vitamins, including folate and vitamin K, which are sometimes scarce in other legumes. Because of these qualities, edamame is positioned in plant-based diets as a legume with excellent nutritional value and functionality. Nutritional parameters of legumes given in Table 1.

Table 1: Nutritional parameters of legumes

Nutritional Parameter	Edamame	Mature Soybean	Chickpea	Lentils
Protein (g/100g)	11–13 *(USDA, 2020)*	35–40 *(Messina, 1999)*	18–21 *(Jukanti et al., 2012)*	9–11 *(Mudryj et al., 2014)*
Protein Quality	Complete *(Young & Pellett, 1994)*	Complete *(Friedman & Brandon, 2001)*	Incomplete *(Jukanti et al., 2012)*	Incomplete *(Mudryj et al., 2014)*
Fat Content (%)	5–7 *(USDA, 2020)*	18–20 *(Messina, 1999)*	5–6 *(Jukanti et al., 2012)*	1–2 *(Mudryj et al., 2014)*
Carbohydrates (g/100g)	8–10 *(USDA, 2020)*	30 *(Messina, 1999)*	27 *(Jukanti et al., 2012)*	20 *(Mudryj et al., 2014)*
Dietary Fiber (g/100g)	4–5 *(USDA, 2020)*	9–10 *(Messina, 1999)*	7–8 *(Jukanti et al., 2012)*	7–8 *(Mudryj et al., 2014)*
Vitamin Content	High *(Haytowitz et al., 2019)*	Moderate *(Messina, 1999)*	Moderate *(Jukanti et al., 2012)*	Moderate *(Mudryj et al., 2014)*
Mineral Content	High *(Weaver et al., 2013)*	High *(Messina, 1999)*	Moderate *(Jukanti et al., 2012)*	Moderate *(Mudryj et al., 2014)*
Anti-nutritional Factors	Lower *(Liener, 1994)*	Higher *(Liener, 1994)*	Moderate *(Jukanti et al., 2012)*	Moderate *(Mudryj et al., 2014)*
Digestibility	High *(Rutherfurd et al., 2015)*	Moderate *(Friedman & Brandon, 2001)*	Moderate *(Mudryj et al., 2014)*	Moderate *(Mudryj et al., 2014)*
Palatability	High *(Miles et al., 2000)*	Low *(Messina, 1999)*	Good *(Jukanti et al., 2012)*	Good *(Mudryj et al., 2014)*

Phytochemical Profile of Edamame

Edamame's functional and nutraceutical qualities are greatly enhanced by the abundance of various phytochemicals found in its immature stage. Because of their antioxidant, anti-inflammatory, and hormone-modulating properties, these bioactive substances which include isoflavones, phenolic compounds, saponins, and phytosterols play critical roles in the prevention of illness and the promotion of health.

Isoflavones

Among the phytochemicals in soybean-based foods, such as edamame, that have been investigated the most are isoflavones. The two isoflavones found are genistein and daidzein, which are classified as phytoestrogens because of their structural resemblance to estrogen (Setchell & Cassidy, 1999). Depending on physiological circumstances, these substances have both estrogenic and anti-estrogenic actions, which affect hormonal equilibrium.By modifying cell signaling pathways and preventing oxidative stress, genistein has been demonstrated to have antioxidant, anti-inflammatory, and anticancer activities (Spagnuolo *et al*., 2015). Similarly, daidzein's function in calcium control and lipid metabolism promotes bone health and cardiovascular prevention (Vitale *et al*., 2013). Cultivar, maturity stage, and processing techniques all affect the amount of isoflavones in edamame (Lee *et al*., 2003).

- **Phenolic Compounds**
- Flavonoids and phenolic acids, two phenolic chemicals found in edamame, are well-known for their potent antioxidant properties. Flavonoids reduce oxidative damage at the cellular level by acting as metal chelators and free radical scavengers (Panche et al., 2016). By neutralizing reactive oxygen species (ROS), phenolic acids like ferulic and caffeic acids strengthen antioxidant defense systems (Heleno et al., 2015).The total antioxidant capacity of edamame is influenced by the synergistic interaction of several phenolic chemicals. Additionally, these substances are linked to a lower risk of long-term illnesses, such as neurological and cardiovascular ailments (Shahidi & Yeo, 2018).
- **Other Bioactive Compounds**
- Edamame includes significant bioactive substances such saponins and phytosterols in addition to isoflavones and phenolics. Saponins are well known for their ability to modulate the immune system and decrease cholesterol. They work by attaching to bile acids and decreasing the intestinal absorption of cholesterol (Francis et al., 2002).By competing with dietary cholesterol for absorption, phytosterols, which share structural similarities with cholesterol, significantly lower blood cholesterol levels (Ras et al., 2014). These substances also have anti-inflammatory and anticancer properties, which increases edamame's usefulness as a nutritious meal.
- **Antioxidant Activity**

Edamame's varied mix of bioactive phytochemicals is primarily responsible for its antioxidant action. According to Lobo *et al*. (2010), these substances work by scavenging reactive oxygen species (ROS), preventing lipid peroxidation, and strengthening the body's natural antioxidant defenses. These systems are essential for preventing oxidative damage to biological components.A number of chronic illnesses, including as cancer, diabetes, and cardiovascular ailments, are mostly caused by oxidative stress, which arises from an imbalance between the body's antioxidant defenses and the generation of free radicals. Because edamame has a strong antioxidant profile, regular intake may help reduce oxidative stress and improve overall health outcomes (Prior *et al*., 2005). Edamame's antioxidant activity is further enhanced by the synergistic interaction of isoflavones, phenolic compounds, and other bioactive elements, making it a remarkable functional food with notable health-promoting qualities showing in Table 2.

Table 2: Edamame's antioxidants, isoflavones, phenolic compounds and other bioactive elements

Category	Compound	Key Functions	Health Implications
Isoflavones	Genistein	Antioxidant, modulates cell signaling	Anticancer, cardiovascular protection
	Daidzein	Phytoestrogenic activity, hormone regulation	Bone health, heart health
Phenolic Compounds	Flavonoids	Free radical scavenging, metal chelation	Anti-inflammatory, neuroprotection
	Phenolic acids (*ferulic*, *caffeic*)	ROS neutralization, antioxidant defense	Reduced oxidative stress
Other Bioactives	Saponins	Cholesterol binding, immune modulation	Reduced cholesterol, improved immunity
	Phytosterols	Compete with cholesterol absorption	Lower LDL cholesterol
Antioxidant System	Combined phytochemicals	Synergistic antioxidant activity	Protection against chronic diseases

Health Implications of Edamame

Edamame's significant content of soy protein, isoflavones, dietary fiber, and unsaturated fatty acids has been linked to a number of health advantages. By improving lipid profiles and lowering blood low-density lipoprotein (LDL) cholesterol levels, these elements significantly improve cardiovascular health and lessen the risk of heart disease (Anderson *et al*., 1995; Jenkins *et al*., 2010). Edamame also has a high fiber content and a low glycemic index, both of which lessen the risk of type 2 diabetes by improving blood glucose management and reducing insulin resistance (Villegas *et al*., 2008).

By altering inflammatory pathways and lowering pro-inflammatory cytokines, bioactive substances including isoflavones and phenolic compounds also have anti-inflammatory qualities (Kim *et al*., 2013). Furthermore, because of their impact on cell proliferation and death, isoflavones like genistein and daidzein have been thoroughly investigated for their anticancer potential, especially in hormone-dependent malignancies like breast and prostate cancer (Messina & Wu, 2009). Edamame's dietary fiber improves intestinal function and fosters a healthy gut microbiome. Short-chain fatty acids (SCFAs), which are necessary for preserving gut integrity and metabolic balance, are produced when gut bacteria digest fiber (Marco *et al*., 2017; Slavin, 2013). When taken as a whole, these characteristics demonstrate edamame's potential as a functional meal for managing and preventing chronic illnesses. All the health benefits of Edamame showing in the Table 3.

Table3: Health Implications of Edamame and Associated Bioactive Components

Health Benefit	Key Components	Mechanism	References
Cardiovascular Health	Soy protein, isoflavones	↓ LDL cholesterol, improved lipid profile	Anderson *et al*., 1995; Jenkins *et al*., 2010
Diabetes Control	Dietary fiber, protein	Improved glycemic control, insulin resistance	Villegas *et al*., 2008
Anti-inflammatory Effects	Isoflavones, phenolics	↓ inflammatory cytokines	Kim *et al*., 2013
Anticancer Potential	Genistein, daidzein	Regulation of cell proliferation & apoptosis	Messina & Wu, 2009
Gut Health	Dietary fiber	SCFA production, improved microbiota	Marco *et al*., 2017; Slavin, 2013

Processing and Its Impact on Edamame

- **Common Processing Methods**

Processing a significant impact on edamame's shelf life and nutritional value indicating in Figure 1. One of the most popular pre-consumption techniques that improves palatability and lowers anti-nutritional elements like trypsin inhibitors is boiling. However, heat-sensitive nutrients, especially vitamin C, may be partially lost as a result of thermal processing and certain phenolic compounds (Rickman *et al*., 2007; Xu & Chang, 2008). Freezing preserves edamame's sensory appeal and nutritional makeup over long storage times, it is frequently used for preservation. While lengthy storage may result in slight decreases in antioxidant activity, rapid freezing helps preserve color, texture, and the majority of bioactive components (Kalt, 2005; Giannakourou & Taoukis, 2003). Another crucial processing method that improves the functional and nutritional qualities of soybean products is fermentation. By transforming isoflavones into more bioactive aglycone forms, fermentation can boost their bioavailability and perhaps enhance their digestion (Frias *et al*., 2008; Granito *et al*., 2005).

Effect on Nutrients and Phytochemicals

Edamame is processed significantly affects the retention and breakdown of minerals and phytochemicals. Thermal processes like boiling can cause water-soluble vitamins and phenolic compounds to seep into the cooking water, reducing their overall concentration (Turkmen *et al*., 2005). However, certain processing methods can boost the availability of bioactive compounds by dissolving complex structures and reducing anti-nutritional factors (Dewanto *et al*., 2002). Freezing preserves the majority of nutrients, however prolonged storage may cause delicate materials like vitamins and antioxidants to progressively decay (Favell, 1998). On the other hand, fermentation improves the nutritional bioavailability of edamame-based products and adds beneficial metabolites including organic acids and peptides. (Hur *et al*., 2014).

- **Storage Stability**

edamame to remain safe and of high quality, storage conditions are crucial. Nutrient stability and microbial development are influenced by variables including temperature, oxygen exposure, and storage time. Shelf life can be increased by slowing down enzymatic activity and avoiding spoiling by freezing and refrigeration (Singh & Heldman, 2001). However, poor storage conditions might result in nutritional degradation, texture loss, and discolouration (Lee & Kader, 2000). edamame's shelf life and nutritional value have been demonstrated to be enhanced by controlled storage conditions such modified atmosphere packaging (MAP) (Caleb *et al*., 2013).The nutritional integrity and functional qualities of edamame are often greatly impacted by the processing and storage techniques used, underscoring the significance of optimizing these circumstances for the greatest possible health benefits.

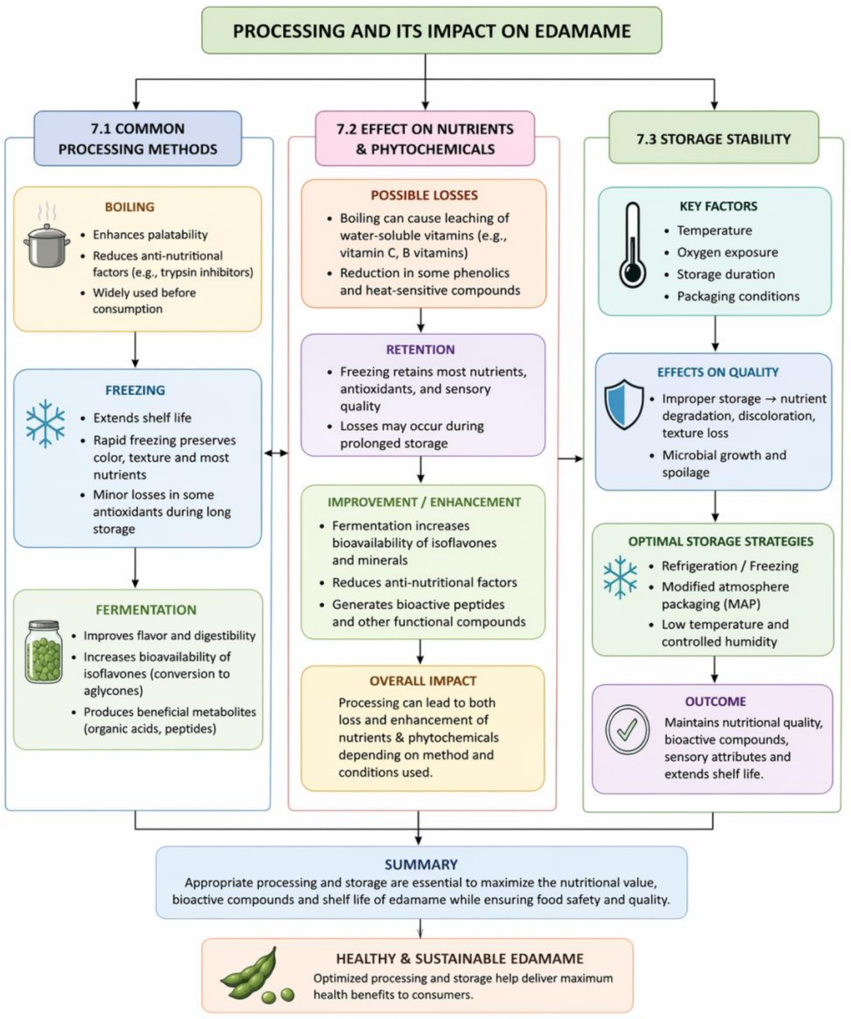

Figure 1: Processing and their impacts on Edamame

Edamame in Sustainable Diets

Edamame, its excellent nutritional content and positive environmental profile, edamame, the immature form of edamame, is becoming more widely acknowledged as a sustainable part of contemporary diets. Compared to animal-based food systems, the production of plant-based foods like edamame often uses less natural resources, such as water and land, and produces fewer greenhouse gas emissions (Poore & Nemecek, 2018). Because of this, edamame is an environmentally friendly protein source that may be used in sustainable food systems. From a nutritional standpoint, edamame is a superior plant-based protein that may successfully help fulfill daily protein needs. It supports its function as a useful substitute for animal protein by supplying important amino acids, dietary fiber, and bioactive substances (Springmann *et al*., 2016). The significance of legumes like edamame in supporting both human health and environmental sustainability has been further highlighted by the growing trend toward plant-based diets. Edamame has a number of benefits over animal protein sources, including as less saturated fat and no cholesterol, both of which are linked to better cardiovascular health outcomes. Furthermore, when it comes to resource consumption and carbon emissions, plant-based protein synthesis has a far less environmental impact (Willett *et al*., 2019). As a result, adding edamame to regular meals is consistent with international guidelines for sustainable and health-promoting eating habits.

Limitations and Research Gaps

Even with the increasing amount of research on edamame, there are still a number of obstacles that prevent a thorough comprehension of its functional potential and health impacts. The scarcity of carefully planned human clinical trials that concentrate on edamame intake is one of the main limitations. According to Messina (2010) and Cassidy *et al*. (2010), a large portion of the information that is currently available comes from in vitro studies or more general soybean-based research, which may not correctly reflect the unique effects of edamame in human populations. The heterogeneity in research results, which might be linked to variations in experimental design, demographic characteristics, dose, and types of soybean products utilized, is another significant issue. It is challenging to get firm conclusions on the health advantages of edamame and its bioactive components because of these discrepancies (Reinwald *et al*., 2010).

Analytical techniques for measuring phytochemicals and evaluating antioxidant activity are also severely lacking in standardization. Disparities in reported data between research are caused by variations in extraction methods, processing conditions, and measurement procedures (D'Archivio *et al*., 2010). This emphasizes how standardized approaches are necessary to increase the reliability and comparability of study findings. To completely demonstrate edamame's position as a functional food and to support evidence-based dietary recommendations, these gaps must be filled by carefully monitored clinical trials and standardized analytical techniques.

Future Perspectives

Edamame's growing uses in nutraceuticals, food innovation, and scientific study are directly related to its promise as a functional food in the future. Edamame presents significant prospects for the creation of nutraceutical products targeted at avoiding chronic illnesses, such as cardiovascular disorders and metabolic problems, because it is rich in bioactive chemicals including isoflavones, antioxidants, and high-quality plant protein. Its economic worth can be further increased by including it into functional drinks and nutritional supplements.

Edamame has a great deal of potential to diversify into value-added products in the food business, including snack foods, protein concentrates, plant-based meat substitutes, and fermented goods. While preserving sensory quality, new processing techniques like fermentation and encapsulation may increase the bioavailability and stability of its bioactive components. Additionally, the incorporation of edamame into contemporary dietary patterns is supported by growing consumer preferences for sustainable and clean-label goods. Well-designed human clinical trials should be the main focus of future research in order to determine optimal intake amounts and unambiguous health benefits. To guarantee uniformity between investigations, standardization of analytical techniques for phytochemical evaluation is also required. Additionally, investigating the relationships between gut microbiota and edamame components may offer fresh perspectives on its functional characteristics. All things considered, edamame has a great potential to support the development of functional food systems and sustainable nutrition.

Conclusion

In order to sum up, edamame is a food that is both nutritious and useful, and it has a great deal of potential to improve human health. In addition to a variety of micronutrients, this review emphasizes its balanced macronutrient profile, which includes dietary fiber, healthy fats, and high-quality protein. Its antioxidant, anti-inflammatory, and disease-preventive qualities are attributed to the presence of bioactive substances such isoflavones, phenolics, saponins, and phytosterols. Additionally, edamame has positive impacts on gut microbiota, glycemic management, and cardiovascular health, which supports its potential to lower the risk of chronic illnesses. Nutrient retention and bioavailability were found to be influenced by processing and storage techniques, highlighting the need of optimal handling. Its minimal environmental effect and function as a plant-based protein source also support sustainable eating habits.

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