*Pavlović, N., Dolijanović, Ž., Simić, M., Kaitović, Ž., Dragičević, V., Brankov, M. (2024). Edamame - Vegetable Crop Of The Future: Production Challenges And Chemical Profile. Agriculture and Forestry, 70 (3): 141-162.* *https://doi.org/10.17707/AgricultForest.70.3.10*

DOI: 10.17707/AgricultForest.70.3.10

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# EDAMAME - VEGETABLE CROP OF THE FUTURE: PRODUCTION CHALLENGES AND CHEMICAL PROFILE

## SUMMARY

Edamame is a vegetable, immature soybean (*Glycine max* [L.] Merr.) and an excellent plant–based protein source which is low in calories, high in essential amino acids, dietary fibre, phospholipids, vitamins, minerals, and many other bioactive compounds. Secondary metabolites in edamame include various phenolic compounds, isoflavones, and saponins. Besides providing fresh, green and highly nutritious beans as the main product, edamame biomass can be utilized at the same time for animal feeding or as green manure. Germination, seedling emergence and stand establishment are very important initial phases in development that have a great impact on the whole vegetative cycle. Weed management is one of the key elements for reaching full genetic and yield potential. Irrespective that edamame could enrich the soil with N through the N–fixation process, optimal nutrition which includes application of mineral and organic fertilizers, biofertilizers as well as foliar fertilizers are required for successful production. Ensuring timely water supply to edamame is another crucial factor that greatly contributes. Edamame, as a vegetable crop, is highly sensitive to environmental fluctuations, thus optimization and the development of adequate cropping technology are essential for successful production. As nitrogen fixing legume rich in bioactive compounds, with various benefits for human health and suitability for crop rotation, edamame hugely contributes to sustainable agriculture.

**Keywords**: germination and emergence; fertilization; weed management; water supply; chemical composition; sustainable agriculture

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Notes: The authors declare that they have no conflicts of interest. Authorship Form signed online.

*Received:00/00/2024* *Accepted:00/00/2024*

# INTRODUCTION

Edamame soybean is a vegetable and a highly nutritious crop, so its presence in the human diet is constantly increasing. Edamame popularity rapidly grows from China and Japan, where it is a common part of the diet. Edamame production is primarily concentrated in China, Japan, and Taiwan, while the main consumers of edamame are China, Japan, Korea, the USA, Taiwan, Thailand, and Europe (Nair *et al*. 2023). China is the biggest edamame producer (Dong *et al.* 2014). The vegetable soybean (or edamame) account approximately 2% of world soybean production (Dar *et al.* 2023). Production technology for this crop is challenging because of several critical points during the vegetation period that can negatively affect edamame development. The important points include the reduced germination rate of the seed, high water demands, sensitivity to pests and weak competition against weeds, through nutrition, up to unequal beans maturation and a short harvesting window governing appropriate storage for maintaining the quality of beans. All of these potentially limiting factors must be mitigated to ensure the successful production. Table 1 presents an overview of the various studies which aimed to deal with some of the challenges mentioned.

Different numbers in superscript next to the surnames of authors represent specific areas covered by the scientific paper. The scientific paper does not have to cover all the specific areas listed under the same letter.

$^{1}$ sowing/planting; $^{2}$ plant nutrition; $^{3}$ weed management; $^{4}$ irrigation; $^{5}$ harvesting and processing, $^{6}$proteins, carbohydrates, lipids; $^{7}$fibers and macro/micronutrients; $^{8}$isoflavones and pigments; $^{9}$vitamins, amino acids, $^{10}$ antinutrients; $^{11}$ chlorophyll and enzymes

$^{*}$This study refers to abiotic stresses (photoperiod, temperature and water) soybean is a light–sensitive plant that has a specific physiological response to the duration of daylight in a 24–hour cycle. It is a short–day plant, therefore it requires shorter daylight period that have to fall below a critical threshold to induce flowering. Sunlight controls duration of pod filling and ageing of leaves (Staniak *et al.* 2023). Day length and light intensity contributes significantly to crop development, growth and yield (Jankauskiene *et al.* 2021). Temperature is the key factor dictating when flowers will appear after floral induction (Heatherly and Elmore 2004). Even with optimal temperature conditions, if the day length is not short enough it will postpone the start of reproductive development (Setiyono *et al.* 2007). This is of particular importance when edamame yield potential is considered. Contrary, sowing edamame (commonly determinant in plant growth) when duration of daylight is too short, will induce flowering during the early vegetative stages, growth will be stopped and developed plants will be stunned, overall resulting in low yield. High temperatures in early spring combined with sufficient sun radiation will induce earlier flowering, thus prolonging duration of reproductive stages and in all positively affect yield (Cooper 2003), in indeterminate soybeans. The longer the vegetation period, the more nodes and pods per plant are formed, and total fresh pod weight is increased (Zhang and Kyei-Boahen 2007).

**Table 1.** Edamame soybean research around the world

| **Technology production** | **Chemical composition** | **Technology production + Chemical composition** | **Reviews** |
|---|---|---|---|
| Duppong, (2005);[4] | Sikka *et al.* (1978);[6, 7] | Simmone *et al.* (2000);[5; 8] | Ravishankar *et al.* (2016);[1, 5-9] |
| Zhang and Kyei-Boahen (2007);[1] | Yanagisawa *et al.* (1997); [9] | Rao *et al.* (2002);[1, 6, 9] | Zeipina *et al.* (2017);[1, 2, 6, 9] |
| Pornprom *et al.* (2010);[3] | Kumar *et al.* (2009);[8, 9] | Carpenter, (2007);[1, 6, 8] | Zhang *et al.* (2017);[1-6, 8] |
| Sharma and Kshattry (2013);[1] | Li *et al.* *(2012);*[6] | Saldivar *et al.* (2010);[5, 6, 10] | Miles *et al.* (2018);[1-5] |
| Li *et al.* (2013);[1] | Carson *et al.* (2012);[8] | Carson, (2010);[1, 6, 8] | Djanta *et al.* (2020);[1-3, 5-9] |
| Williams and Nelson (2014);[3] | Song *et al.* (2013);[6, 9] | Carson *et al.* (2011);[1, 6] | Nair *et al.* (2023);[1-9] |
| Kering and Zhang (2015);[1] | Xu *et al.* (2016);[6, 9, 10] | Santana *et al.* (2012);[5, 6, 8, 9, 10] | Staniak *et al.* (2023);[*] |
| Abugho *et al.* (2015);[3] | Liu *et al.* (2019);[6-9] | Li *et al.* (2014);[1, 9] | |
| Ogles *et al.* (2016);[1] | Carrão-Panizzi, (2019);[6, 8] | Maruthi and Paramesh (2016);[2, 6] | |
| Crawford, (2017);[1, 3] | Jiang *et al.* (2020);[6] | Nolen *et al.* (2016);[1; 6] | |
| Williams *et al.* (2017);[3] | Hertamawati and Rahmasari (2021); [6, 9] | De Oliveria *et al.* (2019);[2, 6, 7] | |
| Williams and Bradley (2017);[3] | Yu *et al.* (2021);[6, 9] | Shiu *et al.* (2020);[4, 5, 9] | |
| Crawford and Willams (2018);[1] | Guo *et al.* (2022);[6, 9] | Jankauskiene *et al.* (2021);[1, 6, 7] | |
| Crawford and Willams (2019);[1] | Agyenim-Boateng *et al.* (2023);[6-9] | Moloi and Van der Merwe (2021);[4, 6, 9, 10] | |
| Lord *et al.* (2019); [1,5] | | Liu *et al.* (2022);[2, 6, 7] | |
| Williams *et al.* (2019);[3] | | Hlahla *et al.* (2022);[2, 3, 6, 7, 8] | |
| Dhaliwal and Williams (2020);[1, 5] | | Moloi *et al.* (2022);[2, 4, 10] | |
| Carneiro *et al.* (2020);[5] | | Brooks *et al.* (2023);[2, 6, 7] | |
| Chen *et al.* (2021);[4] | | | |
| Fogelberg and Mårtensson (2021);[1, 2] | | | |
| Lestari *et al.* (2021);[2] | | | |
| Hasanah *et al.* (2021);[1, 2] | | | |
| Zeipina *et al.* (2022);[1] | | | |
| Li *et al.* (2022);[3] | | | |
| Saputra and Anggraini (2022);[2] | | | |
| Simiderle *et al.* (2022);[2] | | | |
| Netty, (2023);[2] | | | |

Since environmental factors are crucial for edamame production, many researchers evaluated growth of edamame in different agroecological conditions. Jankauskiene et al. (2021) evaluated the potential of growing edamame varieties in Lithuania as a country with a lack of heat and light). The temperature varied approximately from 14°C in May to 18°C in August and precipitation was around 240 mm during the growing season. Five out of six varieties were suitable for Lithuanian climatic conditions. Vegetation period lasted 105 days to the end of R7 stage. They stated that temperature and precipitation were positively correlated with plant height, while better branching of some varieties didn't enhance yield. The yield was correlated with weather conditions and variety. The variety 'Chiba Green' was the most suitable for cultivation under Lithuanian climatic conditions, with the lowest plant height, but the highest yield, the weight of 100 pods, photosynthetic intensity and chlorophyll index. Furthermore, Nolen *et al.* (2016) proved the possibility to grow edamame in Virginia, USA, in early spring, by sowing it in high tunnels, providing optimal temperature conditions for plant development. Ogles *et al.* (2016) investigated characteristics of different edamame cultivars from III to VI maturity group (MG) grown in Central Alabama, USA, during 2014–2015 growing season. Eleven cultivars were investigated. Yield in 2014 was higher than in 2015, which was owing to higher air temperatures (about 33°C) during the R1 stage. In 2014 pod yield varied from 10.2 to 16 t/ha, while next year it varied from 2.6 to 13.5 t/ha. Number of pods per plant was related to maturity group – earlier MG, lower number of pods per plant.

## Differences between edamame and conventional soybean

Unlike conventional soybeans, whose mature beans are commonly used for livestock feed and for processing in various industries, edamame is regularly used as a vegetable. Edamame is a determinant soybean and the main difference between edamame and common soybean is the harvesting time (Zeipina *et al.* 2017). Common soybean is harvested at the R8 stage of development (full maturity), while edamame is harvested earlier, in the R6 stage (full seed) (Figure 1). It is very important to perform harvesting during the period when the pods are green and avoid discoloration to yellow (Zeipina, 2017). At the full seed stage beans take 80–90 % of pod width (Konovsky *et al.* 2020). Any delay in the harvest, pods are turning into yellow and quality is declining. Edamame reaches the full seed stage 75–100 days after sowing (Zeipina *et al.* 2017), depending on a maturity group. There is a difference in the storage conditions needed for edamame and conventional soybeans. Edamame, being harvested with higher moisture content, requires specific handling and storage conditions to maintain its quality. Common soybeans, with a low moisture content (10–13 %) can be stored for a long time without quality degradation, while edamame, with a moisture content of 80 %, has a shorter shelf life (Crawford, 2017). Cooling immediately after harvesting is significant for preserving beans freshness and they are mainly stored in freezers. According to Saldivar *et al.* (2010) when stored in bags with air at 4 °C, the appearance of the edamame remained relatively unchanged, while storing at 25 °C in open air conditions led to significant changes, such as yellowing, browning, shrinking, and wilting. The study also showed that storing edamame pods in a nitrogen atmosphere at 25 °C caused a rapid decrease in the levels of all soluble sugars. Overall, the research concluded that maintaining a low temperature during storage is more crucial than atmospheric conditions in preserving the nutritional and sensory qualities of fresh edamame pods. Maintaining post–harvest seed quality becomes challenging because of high respiration rates (Nair *et al.* 2023). Therefore, storage practices such as blanching, freezing, and storing at low temperatures need to be implemented shortly after harvest. Blanching and storing at low temperatures preserve the high sugar concentration. While the yellow color of the pod is a sign of converting sugar to starch, increasing the maltose content by boiling is a way to maintain and improve the sweetness of edamame seeds (Nair *et al.* 2023).

**Figure 1**. Edamame soybeans (left hand side: VE to VC; middle: R2; right hand side: R6). *VE – growth stage when the coleoptile breaks through the soil surface. VC – cotyledons have been pulled through the soil surface. R2 – the plant is beginning full bloom. R6 – the “green bean” stage, total pod weight peaks. Org. photos.

The differences between the nutrient profile of edamame and common soybeans are expected considering genotype differences as well as the fact that the moment of harvest occurs at different stages. According to Carson *et al*. (2011) the lipid content is lower in edamame, the protein content is similar to common soybean and varied 12.9-18.4 g/100g and 36.1-39.5 g/100 g, respectively. Compared with conventional soybeans, edamame is richer in vitamins and other valuable nutrients. Edamame contains more vitamins A, C, K and, B than common soybean (Takahashi and Ohyama 2011). Edamame has higher content of Fe while common soybean has higher level of crude fat (Sikka *et al.* 1978). Edamame soybean harvested at the R6, contained higher concentration of asparagine, alanine, and glutamic acid compared to common soybean harvested in the same development stage (Yanagisawa *et al*. 1997).

Edamame has a lower content of trypsin inhibitor, as well as cysteine, and methionine in proteins (Nair *et al.* 2023). According to Tsou and Hong (1991) edamame, compared with grain soybean, has higher level of starch (83.20 vs. 0.66 mg/g), total sugar content (110.2 vs. 102.4 mg/g) sucrose (95.14 vs. 62.05 mg/g), glucose (13.4 vs. 11.18 mg/g) and fructose (8.95 vs. 0.73 mg/g), and lower level of raffinose (0.16 vs. 14.85 mg/g), stachyose (0.95 vs. 25.38 mg/g) and crude fiber (44.9 vs. 52.7 mg/g) measured on dry weight basis.

A production process of edamame is similar to that of conventional soybeans, with slight differences such as plant density and harvest time. Optimal plant density reduces competition among plants, allowing them greater access to water, nutrients, and sunlight accessible, which overall increase photosynthesis efficiency (Staniak *et al.* 2023). Providing enough space for development is important for edamame soybeans, which branch more than common soybean (Zeipina *et al.* 2022). Edamame seeds are larger, therefore the recommended sowing distance in the row is greater and the planting density is lower (Zeipina et al. 2017). These results in a lower plant density compared with common soybeans, which also provide more space for weeds. Sharma and Kshattry (2013) stated that branching is positively correlated with number of pods. Lower plant density affects greater branching and pod number, resulting in a higher yield, while at higher densities, fewer pods and branches are formed and thus, the yield is lower (Dhaliwal and Williams 2020). According to Hasanah et al. (2021) spacing of 20 x 20 cm significantly reduced the number of productive branches per plant on edamame on 5.8. At a spacing of 30 x 20 cm, it increased to 6.6, while at 40 x 20 spacing, there were 6.4 productive branches per plant. Zhang *et al.* (2013) concluded that common soybean had better emergence than edamame because it is less sensitive to deeper planting. On 3 cm depth, edamame and common soybean had equal emergence rate, while on deeper planting depth (4 and 5 cm), edamame had lower emergence rate.

Due to its short vegetation period, edamame is suitable for multiple cropping during the same year (double or triple cropping), depending on maturity group, climate and latitude. However, taking all the mentioned factors into account, introducing edamame varieties for the first time can be challenging and it may be difficult for farmers to achieve the expected yield and quality (Djanta *et al.* 2020).

## Seed quality and vigor of edamame

High–quality seed is the primary prerequisite for successful agricultural production. Good germination and strong seedling establishment are crucial for successful seedling adaptation to environmental conditions, overcoming stress factors and efficiently utilizing available resources (Cardarelli *et al.* 2022). Seed treatments with microorganisms are beneficial for crops sown directly in the field, such as soybeans, whose development and yield potential strongly depend on symbiosis with microbes (Cardarelli *et al.* 2022).

Kering and Zhang (2015) indicated that for common soybean germination and emergence, soil moisture status has greater importance than seed size. They concluded that under insufficient moisture levels, neither small nor large seeds can finish the initial seed development phases. Crawford and Williams (2018) stated that seed size did not have an influence on edamame crop emergence. Emergence from small seeds was 7.6 % while from large seeds it was 76.8 %. Williams and Bradley (2017) stated that common soybean had better emergence than edamame. Also, seed size affected emergence because smaller seeds need less time to emerge. Williams et al. (2019) noticed 7.2 % higher emergence of standard soybean compared to edamame soybean (67.7 vs. 60.5 %). According to Crawford and Williams (2019), total emergence remained consistent across various seed sizes, but the small seeds had 10 % faster emergence compared with the large seeds, such as edamame have.

The temperature, moisture, and oxygen status of the soil affects seed development and can limit seedling development outside of the optimal range (Li *et al.* 2022). The fastest emergence of three tested edamame cultivars was at 22 °C, while at 10° C, plants weren't able to emerge (Fogelberg and Mårtensson (2021). Initial development stages of edamame (from germination to VE) was postponed up to 17 days after sowing under unfavourable soil conditions including cold and overly moist soil (Sharma and Kshattry 2013). Seed vigor is crucial for germination and emergence and depends on a greater extent on appropriate harvest and storage management (Li *et al.* 2022). Mechanical damage to edamame seeds leads to a decrease in germination, therefore, it is important to handle the seeds with the utmost care during planting to avoid seed injury (Miles *et al.* 2018). Edamame seedlings are also sensitive to damage influenced by penetration through the soil and pest attacks. To maintain high germination rates conditions during storage, play important role (Ravishankar *et al.* 2016). Appropriate fertilization system can increase low germination (Maruthi and Paramesh 2016)

The seed coat has a protective role against biotic and abiotic stress and it controls the speed of seed hydration, slows down imbibition, reduces the risk of injury to dry seeds, and, through thickness, it could induce dormancy and slower germination, which is of particular importance for edamame (Li *et al.* 2022). From this standpoint, some practices, such as cover crops, can reduce edamame emergence because of lower contact between the seed and the soil (Crawford *et al.* 2018*)*.

### Edamame cropping

The main problems in edamame production, includes the high pressure of diseases and pests, leading to increasing use of pesticides, a deficiency of germplasm material (a bottleneck) and a high-water demand (Nair *et al.* 2023). To obtain the maximum genetic potential of edamame soybeans, it is necessary to implement every required practice that will result in the expected yield and quality.

### Weed management

To control weeds in edamame, there are many practices like crop rotation, rotary hoeing, inter–row cultivation, herbicide use and extensive hand weeding

(Zhang *et al.* 2017). After sowing first six weeks is crucial weed control (Sharma and Kshsttry 2013). If pre-emergence herbicides effectively manage weeds, it is possible to avoid post-emergence herbicides (Pornprom *et al.* 2010). Pre-emergence herbicides help plants in competition, prevents weeds from becoming too large to control and give the possibility to reduce the use of chemicals, costs, and environmental harm (Pornprom *et al.* 2010).

Many published studies are related to weed control using herbicide (Pornprom *et al.* 2010; Abugho *et al.* 2015; Williams and Nelson 2014; Williams *et al*. 2017; Crawford and Williams 2018; Williams *et al*. 2019), and only a few of them are related to environmentally friendly practices (Crawford *et al.* 2018; Crawford and Williams 2018). In the future more attention needs to be paid to evaluation of integrated weed management practices in edamame production, which include combined implementation of cultural, mechanical, biological, chemical, and preventive strategies to control weeds.

Williams and Nelson (2014) investigated tolerance of edamame and commom soybean to bentazon, fomesafen, imazamox, linuron, and sulfentrazone, indicating linuron and fomasafen as the friendliest herbicides for edamame. Results obtained from Crawford and Williams (2018) study showed that edamame plants, developed from larger seeds, in the presence of *Abutilon theophrasti*, were taller, produced 7.5 % more biomass and had higher LAI, than those from smaller seeds, in the early stages of growth, two to eight weeks after emergence. Williams *et al*. (2019) evaluated tolerance of edamame on application of pre-emergence herbicides consisted of flumioxazin as well as its mixture with chlorimuron, metribuzin, acetochlor, and pyroxasulfone (not registered for weed control in edamame). Research included edamame cultivars as well as standard soybean cultivars. For edamame, injuries from flumioxazin-based treatments, 2 and 4 weeks after treatments were 2.9 % and 0.9 %, while for common soybean it 1.7 and 0.7 %, respectively. Crawford *et al.* (2018) investigated the impact of different cover crops (winter–killed oilseed (*Raphanus sativus* L.), two *Brassica napus* L. treatments early–killed and late–killed, two *Secale cereale* L. treatments early–killed and late–killed, and bare–soil control) on soil moisture level, edamame emergence, weed density, and weed biomass. The results indicated that cover crops preserved soil moisture by reducing evaporation. Among the tested cover crops, late–killed *Seccale cereale* preserved the highest amount of water, while edamame emergence had the lowest value. Early–killed *Secale cereale* reduced weed density by 20 % and suppressed early–season weed growth by 85 %, indicating it as the best solution for weed management.

**Fertilization**

A commonly used practice to enhance soybean growth is seed inoculation with biofertilizers, i.e., microorganisms which can increase the availability and supply of nutrients. It is not necessary to inoculate seed with biofertilizer every year and in some cases, microbiological fertilizers might express even a negative effect on yield (Fogelberg and Mårtensson 2021). Also, essential macro- and microelements can be provided during the vegetation period, through foliar fertilization or fertigation. By application of foliar fertilizer, it is possible to supply the plant with micronutrients (Brankov *et al.* 2020), especially when nutrient availability in the soil is limited (Fernández and Brown 2013). It is important to underline that foliar fertilization allows the addition of nutrients in small quantities (Patil and Chetan 2018), while the plant's response is faster compared with soil application (Fageria, 2009). It is important to mention that biofertilizers and foliar fertilizers cannot exclude or replace the use of mineral fertilizer, but serves as supplement to maintain plant nutrition on optimal level.

Maruthi and Paramesh (2016) investigated the effect of different fertilization systems on the edamame quality finding that the best emergence and seed quality parameters were achieved in the treatment that included the full NPK rate + the full rate of farmyard manure + *Bradyrhizobium* + PSB. Compared with the treatment that included only the full NPK rate, the combined treatment had 12.4 % higher field emergence and 2.0%t more protein. Thus, a higher nutrition rate promotes seed quality, increasing nutrients reserve in seed. In South Asia, edamame was involved in an intercropping system and it can reach yields of up to 10 t ha$^{-1}$ (Ravishankar *et al.* 2016). The edamame residues can improve soil nutritional status, nitrogen by 129 kg ha$^{-1}$, potassium by 21 kg ha$^{-1}$ and organic carbon by 0.09 percent (Ravishankar *et al.* 2016). Deficiency in essential nutrients such as Zn could result in poorer growth, yield potential, and bean quality. De Oliveira *et al.* (2019) examined different methods of Zn fertilization (application on the soil; foliar application at V4; V8 or R4 stage). Compared with other treatments, foliar application of Zn at R4 influenced the greatest accumulation of Zn in edamame beans which concentration reached 45.05 mg/kg. The highest mean protein content from all of three cultivars was under R4 (42.3%). Moloi and Khoza (2022) examined the effect of foliar selenium application on the photosynthetic capacity, antioxidative enzyme activities, and yield parameters of a drought–susceptible edamame cultivar. Foliar applied selenium at the V1 increased the level of photosynthesis at the vegetative stage, as well as antioxidative capacity at the flowering stage. Netty (2023) investigated how different rates of organic (compost: 10 or 20 t/ha) and inorganic fertilizers (Urea, SP-36 and KCl – in 100, 75, 50 or 25 % of the recommended rate) complement each other in purpose to enhance plant growth and yield. Compared with the control treatment (100 % inorganic fertilizers), 10 t/ha of compost + 50 or 75 % of inorganic fertilizer was the most effective in enhancing plant height, total number of leaves per plant and number of productive branches. Brooks (2023) evaluated the effect of different date (at-planting and split 50% applied at-planting and 50% at R1) and amount (22.4, 44.8, 67.2 and 89.6 kg N/ha) of nitrogen fertilizer, as well as S fertilizer (22,4 kg/ha), on yield, nutrient uptake, C, N, and S concentrations in plant tissue, chemical and physical quality of edamame. In two of three tested years, for every kg of Nitrogen added in soil yield increased 8.98 kg/ha and 29.9 kg/ha. Application of different fertilization treatments didn’t have influence on content of N, C, S C:N, C:S ratio in plant tissues. Uptake of N, C and S. N uptake was higher than applied amount of N fertilizer, while S uptake was lower than applied amount.

**Crop arrangement and sowing date**

The sowing date had a strong influence on yield. Zeipina *et al.* (2022) tested the possibility of growing edamame soybeans at higher latitudes by combining different cropping practices. They tested direct edamame sowing in the field and production of transplants in a greenhouse and then sowing in the field) and plant densities (13 plants m$^{-2}$ and 20 plants m$^{-2}$). The growing season and sowing method had a significantly affected the yield. Among two tested cultivars, both reached the highest yield at higher plant density and production in the greenhouse. The results of these studies indicate that is possible to successfully produce edamame in tested region which has specific climate conditions. Li *et al.* (2014) conducted a study in Harbin, China to test the impact of different sowing date (3 May, 15 May, 27 May, and 8 June) on fresh pod yield and chemical composition of edamame beans. It was shown that with delayed sowing date, the fresh pod yield and the content of oil and sucrose was decreased. They documented that late sowing increased the protein accumulation, free amino acids and the content of glucose and fructose. The content of raffinose and stachyose, which are characterized as anti-nutrients was also increased with delaying sowing date.

**Water requirements of edamame**

Generally, soybean has high water demands during the vegetation period, as indicated by the transpiration coefficient that ranges from 600 to 700 L, making soybean an inefficient water consumer (Hrustić *et al.* 1988). Edamame as a determinant soybean is more sensitive to water deficit than standard soybean. Soybean is especially sensitive to water deficiency during germination, flowering, pod formation, and bean filling. However, between seed emergence and flowering, soybeans are less susceptible to water stress. During imbibition, seeds need to absorb water in 90–150 % of their dry mass to germinate (Hrustić *et al.* 1988). What is more, 65 % of the total water requirement for the entire vegetation period is consumed during the flowering, pod formation and bean–filling stages (Kranz and Elmore 2022). Hrustić *et al.* (1998) found that optimal photosynthesis could be achieved only if cellular turgor is maintained by an adequate water supply, while the water deficit and decrease in turgor pressure thereby reduce net assimilation, overall organic matter production and agricultural yield.

Research by Mertz-Henning *et al.* (2017) showed that the greatest decrease in soybean yield occurred when the water deficit stress happened during the reproductive stage. Moreover, it was observed that protein content was higher while oil content was lower in plants exposed to a water deficit during the reproductive stage. Drought also leads to a reduction in the number of nodes and internodes length (Hrustić *et al.* 1988). The level of soil moisture significantly impacts the flowering intensity, pod quantity, and plant height of edamame

(Zeipina *et al.* 2022). Drought stress during the flowering stage decreased the edamame yield, qualification rate (relation between total pods and fully filled green pods without shape abnormalities) and qualified pod dry weight, while the total number of pods per plant was not significantly affected (Chen *et al.* 2021). Furthermore, Moloi and Khoza (2022) concluded that drought stress reduces the photosynthetic capacity, antioxidative enzymes and yield of edamame. They examined the response of edamame soybean on applied selenium foliar fertilizer and drought stress (30 percent water holding capacity) occurred at V3. Owing to pronounced sensitivity to drought of edamame, Hlahla *et al.* (2022) tested the biochemical response and detected the compounds which may serve as indicators of drought tolerance in different edamame cultivars sensitive or tolerant to drought stress. Cultivars were exposed to drought stress at V3 by decreasing water holding capacity of soil from 100 to 30 %. Because of reduction of carotenoids and hemicellulose content, as well stomatal conductance in drought sensitive cultivars and high level of starch in drought tolerant cultivars they stated that those parameters could be indicative factors of drought stress in edamame. According to Moloi and van der Merve (2021), total soluble sugars during the flowering stage and proline during the pod–filling stage has a protective role in edamame during drought stress. Total soluble sugars content increased 1.75-fold, from approximately 1.2 to 2.1 mg glucose/g fresh weight. Proline content increased 2.25-fold (approximately from 0.09 to 0.22 mg /g fresh weight) under drought stress treatment (30% water holding capacity) compared to control (100% water holding capacity), in drought tolerant cultivar.

### Harvest and bean quality

Due to the fact that malnutrition (hidden hunger) is a persisting problem worldwide, the quality of products containing essential minerals, vitamins, and other bioactive compounds is a requirement for successful agricultural production. Edamame soybeans are a source of protein, amino acids, carbohydrates, vitamins, minerals, antioxidants, fibers, and soflavones. Compared with snap peas and green peas, consuming edamame increases the intake of essential minerals such as iron, zinc, magnesium, phosphorus, calcium, potassium, sodium, copper and manganese are because of their higher concentration in edamame beans (Takahashi and Ohyama 2011). Flavour, texture and sensory traits define the quality of edamame. Sucrose enhances the sweetness, while compounds like saponin, isoflavonoids, and L–arginine contribute to the bitterness (Zeipina *et al*. 2017). Amino acids contribute to edamame giving it a sweet (Ala, Gly, Ser, Thr, Pro) rich (Asp, Glu) or bitter (Arg, His, Iss, Leu, Met, Phe, Val) flavor, while some are neutral (Tyr, Cis, Lis) (Guo *et al.* 2022). Volatile compounds are related to aroma and the main volatile compounds were aldehydes and alcohols (Guo *et al.* 2022). From this standpoint, it is of particular importance to harvest edamame while maintaining the highest bean quality. Moisture content outside the optimal range indicates that the beans are either fully ripened or have not yet reached maturity, making them unsuitable for classification as vegetable and market use (Agyenim-Boateng *et al.* 2023).

Dry conditions during seed maturation will have an enhanced effect on the quality of the beans (Nair et al. 2023).

### Important nutrients in edamame beans

Edamame beans on a dry weight basis contain 40.2 % of proteins, 23.2 % of fatty acids (palmitic, stearic, oleic, linoleic and linolenic acid), with linoleic acid as the most abundant; 7.4 % of total soluble sugars (sucrose, fructose and glucose); 1401.1 µg/100 g of total reduced folates; 12130.7 µg/100 g of total carotenoids (β–carotene, α–carotene, β–cryptoxanthin, zeaxanthin and lutein the most presented); 548.9 µg/g of total tocopheroles content; 1633.5 µg/g of total isoflavones; 1889.1 mg/100 g and 7.38 mg/100 g of Mg, K, and Fe, respectively (Agyenim-Boateng *et al.* 2023). Xu *et al.* (2016) investigated chemical and physical traits of edamame beans, depending on development stage. Accordingly, the intensity of bean green color progressively decreased from the R5 to R6. After R6 it was rapidly transformed to a yellow color, owing to chlorophyll degradation. Protein and lipid content followed seed development and maturation (protein content was gradually increased from 34.8 at R6 to 37.6 g /100g dry weight at R8, while lipid had a period of stagnation around the R6 (17.2 g /100 g dry weight and increased to 18.2 g /100 g dry weight at R8). Further, Liu *et al.* (2019) evaluated different edamame soybean genotypes to compare nutritional compositions of fresh and matured seeds (R6 and R8). Protein concentration varied among genotypes and there was no clear illation, is protein content higher at full maturity stage or at full seed stage. It varied between 34.6–43.9 % at R6 and R8 38.4–42.5 %. Soluble sugar concentration was significantly higher at R8 than at the R6. Content of sucrose was also increased, from 55.6 to 70.5 %. Xu *et al.* (2016) reported that at the R6, edamame had the highest sucrose level and its content was declining through bean maturation. Total sugar content tended to decline from 43.9 at R6 stage to 39.9 g/100 g dry weight at R8. At R1 sucrose level was 6.51 g /100 g dry weight. At R6, sucrose level increased 41 %, while at R8 it increased only 7 % relative to the level in R1. Contrary to this, Santana *et al.* (2012) stated that sucrose level was 44 % higher in R8 compared to R6. Obtained from three cultivars, the mean values of raw fat, raw protein, and soluble sugar content were 18.92, 37.38 and 6.39 g /100 g dry weight, respectively. First two components promote texture, while sucrose contributes to sweetness (Guo *et al.* 2022). Results obtained from Guo *et al.* (2022) indicated that alanine, glutamine, and asparagine are the most represented among analyzed amino acids, with average content 0.92 mg/g, 3.20 mg/g and 1.22 mg/g, respectively. Li *et al.* (2012) confirmed that sucrose takes up 71.7 % of the total sugar content and found a negative correlation between protein and total soluble sugar and sucrose. They also concluded that a protein increase of 10 mg/g is followed by a sugar decrease of 4.3 mg $g^{-1}$, indicating that carbon was in that case involved mainly in protein synthesis regarding sucrose synthesis. According to Liu *et al.* (2019) most abundant mineral element was potassium (16.4-19,3 mg/g). The concentration of K, Na, Zn, and Mn was higher at R6, while Mg and Fe concentration was higher at R8.

### Antinutrients in edamame beans

It is well known that soybean seeds are high in several anti–nutrients, such as phytic acid, trypsin inhibitors, oligosaccharides, phenols, saponins, etc. Phytic acid interacts with minerals, forming insoluble complexes with them (chelation) thus reducing the availability of divalent and trivalent metal ions of Zn, Fe, Ca, Mg, Mn, and Cu (Sharma, 2021) and decreasing their absorption in the digestive system. Despite this, it is worth mentioning the antioxidant effect of phytic acid (Kumar *et al.* 2010). Trypsin plays a key role in protein digestion, so trypsin inhibitors, as protease inhibitors, are considered as an antinutrient in legumes because protease inhibitors may inhibit pancreas growth and enlargement (Gemede and Ratta 2014). Oligosaccharides are also categorized as antinutrients due to their poor digestibility and ability to cause flatulence, a common digestive problem (Sharma, 2021). In edamame, beans are presented raffinose and stachyose. Above mentioned components cannot be entirely deemed as undesirable since, in addition to their antinutritive effects, their positive effects on human health are well-documented.

Xu *et al.* (2016) stated that the level of phytic acid increased significantly during seed development and maturation, whereas in edamame beans, the phytate concentration is lower than in the mature beans (R8). Additionally, total phenolic content had the lowest value at R6 compared to all other reproductive stages. The level of polyphenol thiamine was in stagnation between the R5 and R8, when it reached its maximum. The level of phytate reached the highest value at R8 (11.1 mg/g dry weight), while at R6 it was 43 % lower. Trypsin inhibitor activity was at the highest level at R6. The level of oligosaccharides, as an undesirable trait, started to increase from R1 through R6 and R8. Initial content of raffinose at R1 was 0.08 g /100 g dry weight. At R6 it increased 4.75-fold, while at R8 it increased 12.6-fold, to 1.09 g /100 g dry weight. Stachyose level tended to decrease from 0.36 g/100 g dry weight, at R1 stage, to 69.4 % at R6. However, at R6 it reached significantly higher concentration (5.13 g /100 g dry weight). Contrary, Santana et al. (2012) stated that raffinose did not differed significantly, while stachyose content was 62.9 % lower in R8 compared to R6. Results obtained from Saldivar et al. (2010) were in agreement with results from Xu et al. (2016) regarding to stachyose and raffinose content in mature seeds, but they did not found this oligosaccharides in immature edamame soybean harvested at R6. Results from Santana et al. (2012) showed that level of phytic acid is the highest at R8.

### Bioactive compounds in edamame beans

Bioactive compounds presented in edamame beans are important from a nutritional point of view and also have potential health benefits. Isoflavones from soybeans such as: daidzein, genistein, and glycitein (Peñalvo *et al.* 2004), are biologically active compounds and have many health benefits for humans. They have estrogen–imiting functions and the first two act as antioxidants. It was proven that genistein indirectly inhibits the development of breast cancer cells and soybean isoflavones may help reduce the risk of heart disease (Munro *et al.*

2003). They could also help in the prevention, suppression, or inhibition of prostate cancer, increasing bone density and helping prevent osteoporosis (Munro *et al.* 2003). Carotenoids are considered as bioactive compounds due to their antioxidative activity and health benefits.

Carpenter (2007) reported that total isoflavones content varied from 48.92 to 132.78 µg/g, depending on edamame variety. Among them, the highest concentration had malonyl daidzin 24.8-67.7 µg/g and malonyl genistin 14.3-53.3 µg/g. Concentration of daidzein and genistein was below 1 µg/g, diadzin up to 5.7 µg/g, genistin up to 2.8 µg/g and glycitin up to 1.3 µg/g. Kumar *et al.* (2009) analyzed the content of tocopherols, isoflavones, total phenols, and antioxidant activity in different reproductive stages of common soybean, often used at R6. All four tocopherol isomers were presented in the beans, but at R5 and R6 δ-tocopherol had the highest concentration (39.6 and 44.8 µg/g), respectively. At later stages tocopherol level increased as well as total isoflavones content. The amount of daidzein, glycitein, genistein, and total isoflavones at R6 were 166.16 µg/g, 183.28µg/g, 375.57µg/g and 725.00µg/g, respectively. From R5 to full maturity these components increased 4.6-, 3.12-, 9.6-, and 5- fold, respectively. Free radical scavenging activity, total antioxidative activity, and total phenolic content was at the highest level in immature seeds, and decreased with maturing. Percent of reduction of DPPH radicals decreased from 58.5 % at R5 to 43.9 % at full maturity. According to Carrão-Panizzi et al. (2019) total isoflavones total β-glucosides, total malonyl glucosides, and total aglucones was lower at R6 of edamame compared to R8: 224.84 vs. 475.00 mg/100 g, 22.56 vs. 112.98 mg/100 g, 194.44 vs. 349.04 mg/100 g and 3.74 vs. 13.00 mg/100 g, respectively. In edamame beans, content of lutein and β-carotene, depending on variety, varied from 895 to 2119 µg /100 g dry weigh, and from 291 to 491 µg/100 g, respectively (Simonne *et al.* 2000).

Legumes, characterized by a low glycaemic index and high fiber content, play an important role in reducing in the risks of obesity, diabetes, cardiovascular diseases, cancer and high levels of cholesterol (Sharma, 2021). Two major storage proteins that belong to the globulin family known as glycinin (11S) and β–conglycinin (7S) are the primary sources of protein in soybeans and are considered high–quality proteins due to their balanced amino acid profiles, which provide all essential amino acids, limited only in methionine (Zarkadas *et al.* 2007). Other authors identified edamame as a complete protein source (Hertamawati and Rahmasari 2021, Lord *et al.* 2019). According to Song *et al.* (2013), the content of free amino acids in edamame varied between 4.6 and 10.2 mg $g^{-1}$ dry matter including all 23 amino acids and all essential amino acids are present of 0.5 mg $g^{-1}$ dry matter. Soybean protein is high in lysine, which is typically low in other common crops (Agyenim-Boateng *et al.* 2023). Liu *et al*(2019) reported that concentration of free amino acid was higher at R6 and varied between 74 and 129.2 mg/g. The most abundant amino acids were: arginine, alanine, serine, glutamic acid, and aspartic acid. The content of saturated fatty acid (palmitic acid + stearic acid) was generally higher at R6 while the concentration of unsaturated fatty acid (oleic acid + linoleic acid + linolenic acid) was higher at R8. The gama–aminobutyric acid (GABA) is also reported to be present in edamame beans and the average concentration was 0.437 mg $g^{-1}$ dry matter. Flooding treatment before harvesting can enhance the level of GABA in edamame, without negative consequences on yield (Shiu et al. 2020). Among organic acids, citrate (2.8 mg $g^{-1}$ dry matter) and malate (2.1 mg $g^{-1}$ dry matter) have the highest concentrations and are related to sensory attributes (Song *et al.* 2013). Edamame contains lecithin, an essential component which supports brain development and can enhance memory and cognitive abilities.

### Edamame – part of sustainable diet and sustainable agriculture

Edamame contributes to sustainable agriculture and a sustainable and healthy diet. The soybeans cultivation supports and improves soil fertility by facilitating nitrogen fixation (Agyenim-Boateng *et al.* 2023) through a symbiotic relationship with nitrogen–fixing bacteria, reducing the reliance on mineral nitrogen fertilizers at the same time. Due to its short vegetation, edamame could also be included in rotation as a double crop or even as a cover crop, increasing the status of organic matter and nitrogen. Even more, including edamame soybeans in crop rotation in both organic and conventional production might help break pest and disease cycles. Because of the short vegetation period and simultaneous flowering and grain filling, its biomass could also be successfully used as a feed (Zhang *et al.* 2017), i.e., for forage and silage production. From this standpoint, edamame growing increases crop diversity, fitting into various cropping systems. Due to its richness in protein, dietary fiber, vitamins, minerals and bioactive compounds, edamame has a high nutritional value. Edamame can be eaten fresh, in soups, salads, or as a snack. It can be processed by boiling or roasting (Duppong and Hatwerman-Valenti 2005). Thus, by including edamame in diets, nourishment with essential nutrients is supported (Agyenim-Boateng *et al.* 2023).

On the market, it can be sold fresh or frozen, in pods or as beans. Edamame popularity rapidly grows worldwide. The world population recognizes edamame as a healthy and tasty food. The health benefits distinguish edamame as a specialty food that is part of a healthy and sustainable diet. As a result of above, it is estimated that edamame consumption and market needs will rapidly grow over time, while cropping technology is still evolving. This gives opportunity to agro-science and agro–business to develop cropping practices and genotypes adapted to various agro–climates and expand edamame growth over arable areas.

## CONCLUSION

Based on its unique nutritional profile, edamame soybean has a great potential to be included in healthy and sustainable nutrition, in regard to the standard soybean. Low in antinutrients and calories, but high in protein, vitamins, minerals, and other bioactive compounds which have heath promoting role, it could be concerned to be nutraceutical. Nevertheless, growing edamame as a vegetable crop could be challenging, particularly when weed control and irrigation are considered. Furthermore, as a legume crop, its cropping is beneficial due to the nitrogen fixation. So, from the nutritional and agro-ecological standpoints, edamame is multiple significant, whereas cropping system should be adjusted to the local agroecological conditions.

## ACKNOWLEDGEMENTS

This work was supported by the Ministry of Science, the Republic of Serbia [ED: 451-03-47/2023-01-200040].

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