



Vegetable Soybean [*Glycine max* (L.) Merr.] Breeding Priorities, Production Constraints and Pathways for Future Research: A Review

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ABSTRACT

Vegetable soybean [*Glycine max* (L.) Merrill], commonly known as edamame, is emerging as a premier functional food due to its exceptional nutrient density and health benefits. Harvested at the immature R6 reproductive stage, it offers a superior organoleptic profile-characterized by a softer texture and sweeter flavor compared to grain soybeans. This review synthesized data from global and Indian landscapes, revealing that while East Asia dominates production, a burgeoning interest in plant-based diets is driving global market expansion, with U.S. consumption reaching 30,000 tons annually. The study indicate that vegetable soybean provides a complete protein profile (11%-14% fresh weight), essential fatty acids (linolenic acid at 42.96% of lipid fraction) and significant bioactive isoflavones. However, the study also identifies critical production constraints, specifically regarding seedling establishment. Large-seeded varieties, exhibit physiological vulnerabilities including cracked seed coats, high electrolyte leakage and susceptibility to soil-borne pathogens like *Rhizoctonia solani*. In India, despite the release of varieties like 'Swarna Vasundhara' and 'Karune', adoption is hindered by poor seed germination (often approx40%) and limited cold-chain infrastructure. The importance of this crop lies in its dual contribution to nutritional security and agricultural sustainability through atmospheric nitrogen fixation. Future research must prioritize the development of region-specific, disease-resistant cultivars with enhanced "stay-green" traits and improved seed vigor. In conclusion, by strengthening domestic supply chains and improving seed performance, vegetable soybean can transition from a niche crop to a mainstream high-value commodity, significantly boosting rural livelihoods and the Indian agricultural economy.

Key words: Breeding gap, Edamame, Emergence, Nutrients, Vegetable soybean.

Vegetable soybeans [*Glycine max* (L.) Merrill] (2n=40), a member of the *Fabaceae* family, is gaining attention in agriculture and nutrition science due to their exceptional nutrient density and potential health benefits. It is commonly referred as Edamame (Japan), 'Poot Kong' (Korean), Maodou (China), green soybean, edible soybean (North America and other part of the world). The global edamame landscape in 2024 reflects a highly specialized production footprint, totaling 1.05 to 1.15 million metric tons grown across 210,000 to 250,000 hectares. China remains the leader, with a production volume of 750,000 to 900,000 metric tons and a cultivated area exceeding 180,000 hectares focused on both domestic and global markets. Taiwan as a premium producer, generating 75,000 to 85,000 metric tons primarily for the high-end Japanese export market, while Thailand utilizes roughly 8,000 to 10,000 hectares to support its robust frozen processing industry. In the United States, production has reached 30,000 to 40,000 metric tons to meet growing domestic demand for fresh and frozen products. Meanwhile, Vietnam and other emerging regions contribute an additional 40,000 to 50,000 metric tons, signaling a diversifying global export market for this high-value specialty crop (USDA FAS, 2024; FAOSTAT, 2024; Nair *et al.*, 2023). Unlike field soybeans primarily used for oil extraction and animal feed, vegetable soybean harvested for immature pod or green pod at R6 stage (Gao *et al.*, 2024 and Nair *et al.*, 2023) offering a

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unique flavor, softer texture and a rich source of nutrients. Vegetable soybeans are popular in East Asian cuisines (Shilpashree *et al.*, 2021). Pods can be sold in markets as fresh vegetable, frozen and canned products (Nair *et al.*, 2023) also its gaining traction in global markets as a healthy snack and ingredient particularly among health-conscious individuals seeking plant-based protein sources. The quality of vegetable soybean can be categorized into three key characteristics like eating quality (taste, texture, flavor and aroma), appearance quality (pod size, shape, color and uniformity) and nutritional quality (Wang *et al.*, 2024; Wang *et al.*, 2023 and Zhang *et al.*, 2017). Vegetable soybean provides all essential amino acids with significant levels of dietary fiber, vitamins, minerals and bioactive

compounds such as isoflavones and polyunsaturated fatty acids (Table 1). Despite its potential, production remains concentrated in a few countries, in India, it is still at a nascent stage (Nagalakshmi *et al.*, 2015). Due to its exceptional nutritional composition and unique taste, the cultivation of this crop has experienced a substantial increase in interest across various regions beyond East and Southeast Asia over the past decade (Nair *et al.*, 2023). The crop contributes to agricultural sustainability due to the ability to fix atmospheric nitrogen in association with Rhizobia, enriching soil fertility. There are several challenges and limitations in the production of vegetable soybean such as limited genetic resources, hinder the development of varieties suited to diverse growing regions or tailored to meet local taste preferences, also high water requirement restrict production expansion to areas with sufficient water availability (Nair *et al.*, 2023), seed size, seed coat characteristics and chilling injury also interact to influence soybean emergence and vigor. Seedling establishment is influenced by multiple abiotic and biotic factors. Targeted research and development is needed to overcome production constraints and support sustainable growth in vegetable soybean farming. This review investigates the potential of vegetable soybeans, focusing on the challenges related to the limitations in the production, highlights future research directions, emphasizing that, vegetable soybeans could significantly contribute to Indian agriculture, providing both economic and nutritional advantages for farmers and the nation as a whole.

Global and Indian landscape of vegetable soybean: current trends and insights

Globally, vegetable soybean production is dominated by countries in East Asia, where the top leading producers of

vegetable soybeans are China, Japan and Taiwan, while the primary consumers include China, Japan, Korea, USA, Taiwan, Thailand and Europe (Nair *et al.*, 2023). Thailand and Taiwan are major exporters, supplying frozen Edamame to Europe and North America (Global edamame market review, 2021). According to a case study, awareness among farmer's and efficient contribution can lead to higher productivity and profitability for an example Indonesia faces challenges due to weaker systems for managing orders and deliveries due to inefficiencies in the farmers' groups, whereas in Thailand, structured contract farming approach enhances efficiency and export success (Marimin *et al.*, 2010). Vegetable soybeans have become the second largest soy food consumed in the USA at 25,000 to 30,000 t annually (Nair *et al.*, 2023). Interestingly rising interest in plant-based diets has boosted the demand in the global market, over a period of 20 years in Indonesia, the total harvested area of vegetable soybeans has increased from 30.5 ha to 1417 ha till 2017 in Indonesia due to its demand for export (Nair *et al.*, 2023). In India, the cultivation of vegetable soybeans is concentrated in a few select regions and its overall production remains limited (Ministry of Agriculture and Farmers Welfare, 2020). The "ICAR Research Complex for Eastern Region" and the "Farming System Research Centre for Hill and Plateau Region" in Plandu, Ranchi, Jharkhand, developed the improved vegetable soybean variety "Swarna Vasundhara", which was released by the "Crop Variety Release Committee (CVRC)" for commercial cultivation (Annual Report 2022, ICAR-IISR and Ravishankar *et al.*, 2016). Vegetable soybean variety KBVS-1 (KARUNE) released for cultivation by UAS Bangalore in the year 2021 and recommended for southern zone of India like Andhra Pradesh, Tamil Nadu and few reasons of Maharashtra.

Table 1: Nutritional profile of vegetable soybean (per 100 g fresh weight).

Nutritional profile of vegetable protein (per 100 g fresh weight)			
Nutrient category	Concentration/Value		Scientific reference(s)
Energy	135 kcal		Khan <i>et al.</i> (2023)
Water content	68%-71%		Johnson <i>et al.</i> (1974)
Crude protein	11%-14%		
Total carbohydrates	8.00%		
Total fatty acids	7.81%		
Total lipids	5%-7%		
Dietary fiber	5.00%		
Total sugars	2.47%		Agyenim <i>et al.</i> (2023); Takashaki <i>et al.</i> (2011)
Ash	1.00%		Djanta <i>et al.</i> (2020)
Linoleic acid	21.16% (of lipid fraction)		Agyenim-Boateng <i>et al.</i> (2023)
Linolenic acid	42.96% (of lipid fraction)		Agyenim-Boateng <i>et al.</i> (2023)
Iron (Fe)	18.01% (DV/Concentration)		Agyenim-Boateng <i>et al.</i> (2023)
Zinc (Zn)	11.60% (DV/Concentration)		Agyenim-Boateng <i>et al.</i> (2023)
Bioactive compounds: Isoflavone content			
Cultivar examples	Isoflavone range (Year 1)	Isoflavone range (Year 2)	Reference
BeSweet (292, 2015, 2001) and Midori Giant	144.6-529.2 µg/g	127.2-315.5 µg/g	Carson <i>et al.</i> , 2011

Moreover, despite its nutritional benefits and potential as a cash crop, its cultivation remains constrained by several factors (Patil *et al.*, 2018).

The concentration of isoflavones is highly variable, depending heavily on genotype (variety) and environmental growing conditions. High concentrations of genistein are directly correlated with increased bitterness and astringency in the flavor profile. However, they are also responsible for sensory attributes such as bitterness *via* the stimulation of hTAS2R14 and hTAS2R39 receptors (Roland *et al.*, 2011).

Unleashing the culinary potential of vegetable soybean: Recipes and Health Benefits

Vegetable soybean can be consumed directly as garden pea (Ravishankar *et al.*, 2016) also offers versatile culinary applications (Fig 1). To prepare the boiled snack harvest the pods, boil in water for 7-10 minutes (optionally with salt), then immerse in ice-cold water for 1-2 minutes to stop cooking. Drain and serve cold. For vegetable side dish, try tossing them with olive oil and a light sprinkling of salt. Cooked beans are also a versatile ingredient, for boosting the texture and protein content of salads or mixed vegetables. They are equally valuable in stir-fries and can be incorporated into soup, whether homemade, canned, or dried. It can be processed into soymilk and diverse foods including roasted nuts, yogurts, ice-cream, tofu and tempeh (Fig 1). Isoflavones like daidzein and genistein are

benefiting both plants (by enhancing defense and symbiosis) and humans by supporting hormonal balance, heart health, bone strength and potentially reducing cancer risk (Messina *et al.*, 2001; Lee *et al.*, 2004). According to the Foodstruct (2026) nutrition database, the health benefits of edamame are categorized by its unique nutrient density compared to mature soybeans and other legumes. As a “complete protein,” it provides all essential amino acids necessary for muscle maintenance, particularly in plant-based diet. Unlike dried soybeans, edamame retains Vitamin C and is exceptionally high in Folate (B9), which is critical for DNA synthesis and preventing neural tube defects during pregnancy (Table 3). High levels of fiber and soy isoflavones (genistein and daidzein) work to lower LDL cholesterol, improve lipid profiles and reduce risks of atherosclerosis and hypertension. Its low-glycemic index (GI) ensures stable blood sugar levels, making it ideal for metabolic health. Rich in Calcium, Magnesium and Phosphorus, edamame supports bone mineral density (Table 3). Its isoflavones further help reduce osteoporosis risk in post-menopausal women (Table 2).

Key morphological traits and optimal harvest timing for vegetable soybean

Soybeans, as short-day plants, initiate flowering with long nights. When a soybean plant begins to flowering, they enter the reproductive (R) growth stage, categorized into stages R1 (first flower bloom) to R8 (full maturity) as

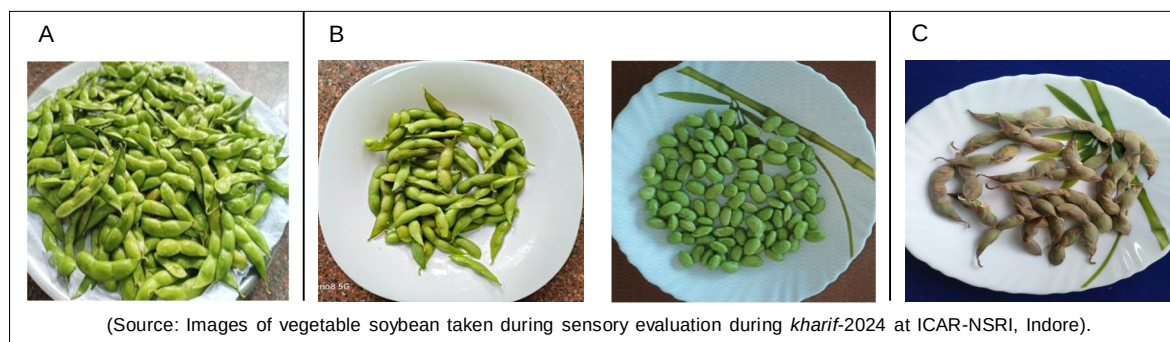


Fig 1: A: Fresh harvested vegetable soybean at R6 stage; B: Boiled vegetable soybean ready to eat (shelled and unshelled pod); C: Roasted vegetable soybean.

Table 2: A comparative analysis of nutrient content in various soybean-derived products.

Product	Serving size	Calories (kcal)	Protein (g)	Total fat (g)	Fiber (g)
Edamame (Cooked)	1 cup (155 g-180 g)	190-254	18-22	8-12	8
Soybeans (Boiled)	1/2 cup	190	7	9	5
Tofu (Firm/Extra firm)	3 oz (85 g)	45-90	9	4	1
Tempeh (Cooked)	1/2 cup	200	18	9	7
Soy milk (Enhanced)	1 cup (243 g)	100-109	7-8	5	1
Soy flour (Defatted)	1 cup (105 g)	394	48	9	17
Soy protein Isolate	1 oz (28 g)	109	26	1	0
Soy burger	1 patty (70 g)	100-124	8-11	4	3

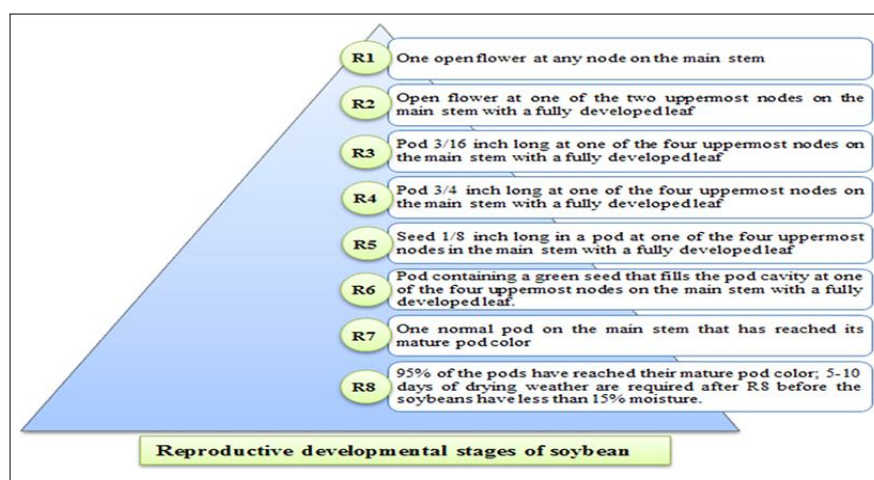
Sources: AAFP, 2009; UC Davis Nutrition Dept, (2018); Sherif, (2013), Nutritional values for tofu, tempeh and edamame products were compiled from USDA Food Data Central (2026).

Table 3: Comparative mineral and vitamin content are estimated per 100 g of soybean-derived products.

Product	Calcium (mg)	Iron (mg)	Magnesium (mg)	Potassium (mg)	Folate (µg)	Vitamin K (µg)
Edamame (Boiled)	63-78	2.2-2.5	64	436-482	303-311	26.7-31
Soybeans (Mature, Boiled)	102	5.1	86	515	54	19
Tofu	350-680*	5.4	58	121	15	2.4
Tempeh (Cooked)	111	2.7	81	412	24	0.5
Soy Milk (Unfortified)	25	0.6	25	118	2	3.0
Soy Flour (Full-fat)	206	6.4	429	1797	305	36

Sources: Agyenim-Boateng *et al.*, 2023; Foodstruct Nutrition Database 2026; Asif and Acharya, 2013; Kumar *et al.*, 2010; Nutritional values for tofu, tempeh and edamame products were compiled from USDA Food Data Central (2026).

*Note: Calcium content in Tofu varies significantly based on the coagulant used (e.g., Calcium Sulfate vs. Nigari).

**Fig 2:** Description and representation of all reproductive developmental stages of soybean (R1 to R8).

indicated in the Fig 2. During stages R1 to R4 plants adjust the number of flowers and young pods based on environmental conditions. Soon after R5 stage it starts to fill the small seeds and continues to begins the R6 stage of the development at this time it is very important to ensure that crop continues to be managed thus it is critical period for irrigation and pest management (Purcell *et al.*, 2021).

Moreover, it is the peak harvesting time for vegetable soybean when the beans reach the R6 stage, with pods 80-90% filled and bright green in color as shown in Fig 3 (a) and (c). Yellowing of pod indicates the physiological changes within seed deterioration of nutritional quality (when sugar converting into starch, consequently changes the taste that is unacceptable to consumers) and unsuitable for fresh market (Zeipina *et al.*, 2017). Vegetable soybean typically matures uniformly, resulting in the entire crop being ready for harvest simultaneously. The peak harvest often lasting just 3 to 4 days (Masuda, 2004), necessitating careful planning and prompt action to ensure optimal quality and yield. Since, pods of vegetable soybean can have 1-3 seeds per pod it can be considered as desirable morphological quality to have at least 2-4 seeds per pod along with large size of pods and seeds with bright green colour. However, texture of the pod (pubescence absent on pod surface) is also a major attribute (Fig 3), which is more acceptable to

consumers because of the clean appearance after cooking (Shanmugasundaram *et al.*, 2015). Additionally, the nutrient content and eating quality like sweetness, texture and flavor is the most desirable.

Progress and challenges in the development of ideal vegetable soybean varieties

Genetic diversity of vegetable soybean and recent advancement

Dong *et al.* (2014) studied 100 vegetable soybean accessions to evaluated genetic diversity and population structure by using 53 simple sequence repeat (SSR) markers and found 98% similarity among the all germplasm collected from China, Taiwan and Japan. Similarly, different researchers also reported the narrow base of vegetable soybean for example (Mimura *et al.*, 2007), also used 17 SSR markers to assessed the diversity of 130 vegetable soybean accessions and observed narrower genetic base of Japanese vegetable soybeans compared to the Chinese vegetable soybeans. Meanwhile, population structure and genetic diversity study in soybean (Chiemeké *et al.*, 2024) shows high and positive contribution of days to 50% flowering, days to maturity, yield, shattering score and lodging score to the total variation. Also phenotype-based core collections (Nair *et al.*, 2023) can retain diversity and

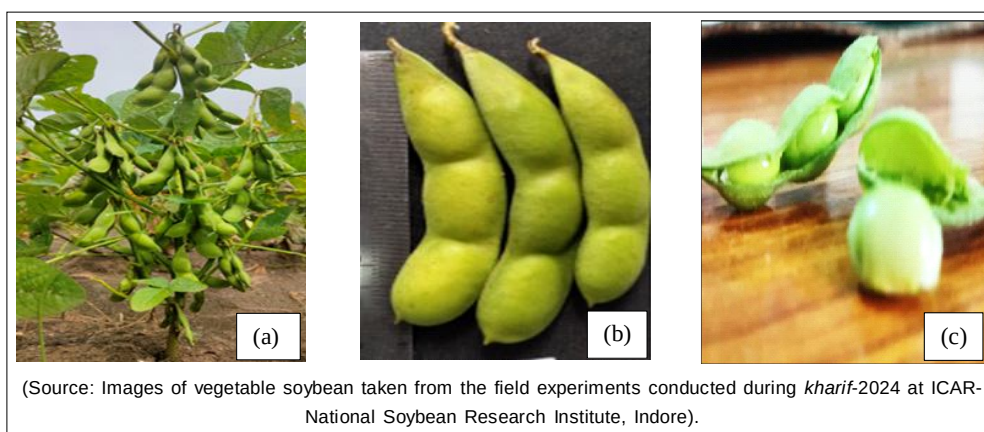


Fig 3: Optimal harvesting stage of vegetable soybean (a) Vegetable soybean plant with 70-80% maturity (b) Image showing pods (c) best for harvesting pod having R6 maturity.

genetic variability of vegetable soybeans, this could be helpful for breeders. Understanding genetic diversity offers essential insights for selecting parents and developing an efficient hybridization strategy. High-throughput phenotyping has been applied to soybean research to study traits such as leaf shape (Chen *et al.*, 2004), root structure (Fenta *et al.*, 2014) and canopy coverage (Xavier *et al.*, 2017). Moreover, (Dhakal *et al.*, 2021) established a phenotyping pipeline for collecting images of vegetable soybean at the harvest stage (R6 to R7) to quantify major shoot architecture traits related to harvest efficiency, including plant height, branching patterns, pod numbers and pod locations. Recently (Gao *et al.*, 2024) conducted a genome-wide association study on 188 vegetable soybean accessions and identified four candidate genes related to pod number of vegetable soybean (Glyma.03g183200), fresh pod weight (Glyma.09G102300 and Glyma.09G102200) and plant height (Glyma.13G109100) from vegetable soybean germplasm. (Yu *et al.*, 2021) re-sequenced the vegetable soybean varieties that are Taiwan-75, Zhexi- andou No. 8, Zhexian No. 9 and Zhexian No. 10, in which cluster analysis using SSR analysis shows the close relationship. Despite of this the average heterozygosity rate of the SNPs was 11.99% among these four, likewise found genetic variation on the chromosomes. Out of 23,371 identified genes a total of 282 genes were related to carbohydrate metabolic processes. These genes and QTLs could help to design the desired type of vegetable soybean varieties through marker-assisted breeding and with help of forward and reverse genetic approaches.

Suitable varieties

In vegetable soybean one of the key challenges limiting the commercial production is the lack of locally adapted varieties (Djanta *et al.*, 2020; Zhang *et al.*, 2013). The World Vegetable Center, Taiwan has developed a significant number of enhanced breeding lines (Nair *et al.*, 2023), have been utilized by various countries to create and release improved and regionally adapted varieties for

cultivation, including North and South America, Europe, Africa (Konovsky *et al.*, 1994; Nair *et al.*, 2023). Countries like Japan and the USA are advancing breeding programs to improve pod size, sweetness, seed uniformity and pest resistance (Kim *et al.*, 2020). These efforts are crucial for meeting the increasing global demand for high-quality vegetable soybean. Recently, seven improved vegetable soybean germplasm lines were released. *i.e.*, LB18-49, LB18-52, LB18-57, LB18-58, LB18-65, LB18-67 and LB18-75, where 'Tohya', 'BeSweet 2001', 'Gardensoy 24' and 'Gardensoy 41' served as recurrent parents with pest-resistant donor lines to develop large-seeded, pest-resistant soybean lines that will be valuable for breeders in the U.S. for developing desired cultivars (Bowen *et al.*, 2022; Nair *et al.*, 2023). More over Researchers found that exotic varieties showed poor seedling emergence in different countries like Australia, the USA and Uganda (Williams *et al.*, 2015; Tsindi *et al.*, 2019) and India (Kuchlan *et al.*, 2023) which indicate that there is need for development of varieties having desirable traits and can grow in the specific climatic conditions. For example, there is a number of variety which introduced from the Japan and Korea were found to be prone to pod shattering which is a concern for seed production in the Midwest USA (Bernard *et al.*, 2001). High pod set for mechanical harvesting are also key goals in China, researchers are initiating to develop better varieties to enhance mechanical harvesting efficiency which includes plant type and height of the lowest pod per plant (Zhang *et al.*, 2017).

Seed characteristics

In china extra-large seed variety (SX6) was identified, which is 40% larger than the slandered variety AGS292 this will be valuable for developing new lines. G10427 is the best genotype specifically for Uganda fulfilling all desired characteristics like large seed size, high yield and adaptability to local conditions (Tsindi *et al.*, 2019). However, main focus on selection by famers is seed germination and storability, because large seed have low germination

due to several factors in this review. Globally consumer preference is also essential for attracting people and ensuring market success, flavor remains a significant focus, emphasizing sweetness and unique taste (for organoleptic acceptance) can be enhanced by the combination of compounds such as ascorbic acid, sucrose, glutamic acid and alanine, with cis-jasmone and (Z)-3-hexenyl acetate also contributing to its desirable taste (Masuda, 1991) and sweetness can be enhanced by increasing the concentration of sweetness-imparting soluble carbohydrates (maltose) in seeds (Nair *et al.*, 2023) targeted breeding strategies can be a promising approach to enhance flavor. Jha *et al.* (2021) reported three QTLs which are proximity of functional genes responsible for biosynthesis of enzymes, which are involved in the breakdown of starch into maltose. It can be potentially useful in marker-assisted breeding for development of high maltose content soybean genotype. Additionally, minimizing pod shatter is critical for seed production, whereas easily opened pods are preferred for fresh consumption. JLM010 a very high yielding vegetable type soybean recommended for Jaboticabal region in Brazil producing fresh weight of 136.04 g of pods per plant and 92.52 g of fresh weight/100 seeds and 11.12 t/ha of total immature seeds (Nair *et al.*, 2023), with better functional properties can be utilized in breeding program for improving pod yield in low yielding lines. In India vegetable type soybean variety namely Karune is released from CVRC system. The main problem to grow this variety in central zone which is hub of soybean is its poor seed germination ability (40%) takes longer time for pod development and even if the field emergence takes place well, the variety is very much susceptible to diseases which drastically reduce the seed production of this variety (Kuchlan *et al.*, 2023). This issue is being addressed at National Institute of Soybean Research Indore, India. Recently NRC 188 has been released for cultivation in central zone of India.

Key constraints limiting vegetable soybean production

Major problem of vegetable soybean is emergence following are the influential factors affecting seed emergence.

Germination and temperature

In vegetable soybean poor germination is a major problem, germination takes about four days at optimal temperatures (27-30°C), whereas it can take two weeks or more in cold soil or about 10°C low temperature (Purcell *et al.*, 2021). Sánchez *et al.* (2005) found that the day/night temperature of 70/60°F ideal for seedling emergence. Hosono *et al.* (2010) conducted a study in Japan and reported that vegetable soybean sown early in the season can be negatively affected by low night temperatures which inhibit seed germination and early seedling development. The study suggested that mulching helps address this issue by increasing soil temperature and minimizing fluctuations in soil moisture. In contrast, in India, high daytime temperatures during the same period can induce thermal stress in crops, necessitating the implementation of

irrigation strategies and the adoption of heat-tolerant agricultural practices to maintain crop growth and productivity.

Seed size

Vegetable soybean seeds are 65-100% larger than grain soybean seeds, influencing hydration, emergence and seedling growth (Crawford *et al.*, 2018). Smaller seeds emerge faster (10%) due to quicker hydration, while larger seeds, requiring more water, are more sensitive to water stress (Rezapour *et al.*, 2013; Kering *et al.*, 2015). Large seeds also face greater soil resistance during emergence, particularly in compacted soils and have higher rates of cracked seed coats (Nangju, 1979), reducing germination potential.

Seed coat characteristics

The seed coat protects the embryo and regulates water uptake, affecting germination and seed longevity. Soybean seed coats are highly hydrophilic, absorbing up to 3.8 times their fresh weight in water (Powell, 1986 and Li *et al.*, 2022). Wrinkles on seed coats or cracks negatively affect the germination (Li *et al.*, 2022), increasing microbial growth and electrolyte leakage (Mohamed-Yasseen *et al.*, 1994). The thickness of the seed coat also affects its permeability, which in turn influences the speed and success of germination (Noodén *et al.*, 1985 and Li *et al.*, 2022). Large seeds often deteriorate faster than smaller ones in the storage longevity of the seeds is influenced by combination of genetics, maturity and quality of the seeds during harvesting timing, moisture content of the seed and storage temperature (Shelar *et al.*, 2008).

Plant depth

Planting depth also affects the seed emergence, deeper planting delays emergence, increases risks like soil-crusting and lowers emergence rates (Crawford *et al.*, 2019). It totally depends on grain type, soil type and weather conditions like rainfall and temperature (Li *et al.*, 2022). Zhang *et al.* (2013) suggested shallower planting around 3 cm is ideal for the vegetable soybean.

Seed and seedling diseases

Soil borne pathogens like *Rhizoctonia solani*, *Fusarium* species, *Phytophthora sojae* and *Pythium* species are common in edamame similar to grain soybeans it can lead to significant yield loss (Williams *et al.*, 2017; Allen *et al.*, 2017 and Xue *et al.*, 2007). Seeds of vegetable soybean with their higher sugar content and larger size leach more nutrients into the soil, attracting pathogens and increasing seedling mortality (Finch-Savage *et al.*, 2016; Li *et al.*, 2022). Fungicide treatments can help but must be used judiciously, especially with increasing interest in organic farming. Biological treatments show promise but need further study. Some bacterial strains, such as *Bacillus subtilis*, "*Pseudomonas putida*", *Streptomyces* species and *Trichoderma harzianum* have shown effectiveness in controlling soil borne diseases and improving seedling emergence in grain soybean

(Reznikov *et al.*, 2016; Paulitz *et al.*, 1992 and Xiao *et al.*, 2002). In India, recently developed varieties like Karune and Swarna vasundhara are susceptible for diseases are a major constraint in the expansion of the vegetable soybean. Additionally, studies on disease resistance in vegetable soybean cultivars have shown varying susceptibility, highlighting the need for further research to develop disease-resistant varieties.

Secondary metabolites in soybean

Secondary metabolites in vegetable soybeans are essential not only for the plant's defense but also for their nutritional content, including protein, lipids, fiber, essential amino acids and micronutrients such as vitamins and minerals (Masuda, 1991). These compounds contribute to the health benefits of soy-based foods. Despite of gaining reputation as superfood it has anti nutritional factors (trypsin inhibitors) that affect the quality and preferences, trypsin inhibitor (TI) has been reported to be present at the R6 growth stage (Kumar *et al.*, 2005) in both grain-type and vegetable soybeans which basically inhibit the activity of "trypsin", an enzyme essential for protein digestion in the small intestine and Kunitz trypsin inhibitor (KTI) is completely synthesized as the soybean plant reaches the R6 stage (Nair *et al.*, 2023). However, KTI is heat sensitive so, it easily inactivated completely by moist heat treatment during cooking or processing due to the presence of only 2-disulfide linkages. In the case of vegetable soybeans, secondary metabolites like flavonoids and phenolics are produced in response to microbial or herbivorous threats, contributing to the plant's defense system and potentially impacting the nutritional profile of the harvested product (Shanmugasundaram *et al.*, 1991).

Quality characteristics impacting the marketability of vegetable soybean

The quality of vegetable soybeans is influenced by a number of factors, such as genotype, harvest timing, crop growth stage and environmental conditions (Mbuvi *et al.*, 1995). Among these, the time of harvest plays a critical role in determining both consumer acceptability and marketability of fresh vegetable soybeans. However, the physical and organoleptic properties are key factors to determine the marketability (Masuda, 1991; Shanmugasundaram *et al.*, 1991). The optimal harvest time (R6 growth stage) is a delicate balance between achieving the best product quality and critical for ensuring yield. Quality traits such as color of pod, texture and seed size are all affected by the development time (Mbuvi *et al.*, 1995). Among physical characteristics, the appearance and size of the pods and seeds are particularly important. High-quality pods are typically bright green and at least 5.0 cm in length and 1.4 cm in width (Kumar *et al.*, 2005). Large seed size (50-60 g/100 pods), glabrous pod and attractive unblemished green colour considered to tempt a premium price in the market. Varieties that align with consumers' taste and culture, like the creamy and beany flavor (preferred by Thai consumers) and

sweetness, large seed (preferred in Australia) can significantly boost acceptance and demand for example variety "Sayamusume appreciated (Ohio State (USA)) for its taste and texture, while Kenko preferred specially because of the pod appearance and sweetness (Wszelaki *et al.*, 2005). Additions to that USA consumer are willing to pay high price for non-GM vegetable soybeans that pointing the interest among consumer preference ranges. Storage facility is the most important factor for the preservation of vegetable soybean, where freezing and refrigerator are the best method to preserve it without losing sensory attributes and nutritional qualities. Blanching before cold storage is an excellent method to improve shelf-life, color, texture and protein stability (Nair *et al.*, 2023).

The future of vegetable soybean research in India

Vegetable soybean (edamame) cultivation in India remains limited, largely due to low consumer awareness and insufficient seed production of vegetable-type varieties, which are often susceptible to diseases. Developing new varieties with better adaptability to Indian agro-climatic conditions and improved resistance to fungal pathogens is essential. There is significant potential for edamame as a nutritious snack and as an ingredient in diverse Indian cuisines, offering considerable opportunities for the food industry. Rising health consciousness in urban areas further positions edamame as a premium, value-added product. Future research should prioritize region-specific, high-yielding varieties with enhanced quality traits such as sweetness, texture, seed size, visual appeal and resistance to insect pests (Kim *et al.*, 2020). Strengthening cold storage infrastructure and supply-chain systems is crucial for supporting a growing market for fresh and frozen edamame products. Additionally, promoting domestic consumption through health-focused campaigns and improving export linkages can help India tap into expanding international markets (Global Edamame Association Market, 2021).

CONCLUSION

Vegetable soybean offers a valuable opportunity for agricultural diversification in India, but its success depends on addressing existing challenges, empowering farmers and strengthening supply chains. Improving seed performance and field establishment requires a thorough understanding of seed emergence issues and their underlying causes. This calls for a multi-pronged strategy in which breeders develop high-vigor cultivars suited to India's diverse edaphic and climatic conditions, supported by optimized seed processing and storage practices. Strategic investments in research and infrastructure can enhance the crop's contribution to nutritional security and rural livelihoods. Moreover, soybean's natural nitrogen-fixing ability positions it as an important component of sustainable farming systems. With the right support, vegetable soybean has the potential to become a profitable, nutritious crop that boosts both Indian agriculture and the broader economy.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this review article.

REFERENCES

- Agyenim-Boateng, K.G., Zhang, S., Zhang, S., Khattak, A.N., Shaibu, A., Abdelghany, A.M., Azam, Qi. J.M., Feng, Ma, C., Feng, H.Y., Liu, Y., Li, J., Li, B. and Sun, J. (2023). The nutritional composition of the vegetable soybean (maodou) and its potential in combatting malnutrition. *Front. Nutr.* **9**: 1-21. doi: 10.3389/fnut.2022.1034115.
- Allen, T.W., Bradley, C.A., Sisson, A.J., Byamukama, E., Chilvers, M.I. and Coker, C.M. (2017). Soybean yield loss estimates due to diseases in the United States and Ontario, Canada. *Plant Health Progress.* **18**: 19-27.
- American Academy of Family Physicians (AAFP). (2009). Soy: A Complete Source of Protein. *American Family Physician.* **79**(1): 43.
- Asif, M. and Acharya, M. (2013). Nutritional and health aspects of soybean. *Journal of Food Science and Technology.*
- Asif, M. and Acharya, M. (2013). Phytochemicals and nutritional health benefits of soy plant. *International J. of Nutrition, Pharmacology, Neurological Diseases.* **3**(1): 64-69.
- Bernard, R.L. (2001). Breeding Vegetable Soybeans in the Midwest. In: *Proceedings of the Second International Vegetable Soybean Conference*, Tacoma, WA, USA. pp. 21.
- Bowen, R., Bardeau, A., Schultz, S. and Hartman, G.L. (2022). Registration of seven disease and pest resistant vegetable soybean germplasm lines. *J. Plant Regist.* **16**(2): 438-445.
- Carson, L.C., Freeman, J.H., Zhou, K., Welbaum, G. and Reiter, M. (2011). Cultivar evaluation and lipid and protein contents of Virginia-grown edamame. *HortTechnol.* **21**(1): 131-135.
- Chen, Y. and Nelson, R.L. (2004). Evaluation and classification of leaflet shape and size in wild soybean. *Crop Sci.* **44**(2): 671-677.
- Chiemeke, F.K., Olanmi, B., Agre, P.A., Mushoriwa, H., Chigeza, G. and Abebe, A.T. (2024). Genetic diversity and population structure analysis of soybean [*Glycine max* (L.) Merrill] genotypes using agro-morphological traits and SNP markers. *Genes.* **15**: 1373.
- Crawford, L.E. and Williams, M.M. (2018). Role of edamame (*Glycine max*) seed size in early-season crop-weed interactions. *Weed Sci.* **66**: 746-751.
- Crawford, L.E. and Williams, M.M. (2019). Planting depth and seed size affect edamame emergence individually. *HortScience.* **54**(1): 92-94.
- Dhakal, K., Zhu, Q., Zhang, B., Li, M. and Li, S. (2021). Analysis of shoot architecture traits in edamame reveals potential strategies to improve harvest efficiency. *Front. Plant Sci.* **12**: 1-13. doi: 10.3389/fpls.2021.61492614926.
- Djanta, M.K.A., Agoyi, E.E., Agbahoungba, S., Quenum, F.J.B., Chadare, F.J., Assogbadjo, A.E., Agbangla, C. and Sinsin, B. (2020). Vegetable soybean, edamame: Research, production, utilization and analysis of its adoption in Sub-Saharan Africa. *J. Hort.* **12**(1): 1-12.
- Dong, D., Fu, X., Yuan, F., Chen, P., Zhu, S., Li, B., Yang, Q., Yu, X. and Zhu, D. (2014). Genetic diversity and population structure of vegetable soybean [*Glycine max* (L.) Merr.] in China as revealed by SSR markers. *Genet. Resour. Crop Evol.* **61**: 173-183.
- FAOSTAT. (2024). Food and Agriculture Organization Corporate Statistical Database. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. <https://www.fao.org/faostat/>.
- Fenta, B.A., Beebe, S.E., Kunert, K.J., Burridge, J.D., Barlow, K.M., Lynch, J.P. and Foyer, C.H. (2014). Field phenotyping of soybean roots for drought stress tolerance. *Agron.* **4**(3): 418-435.
- Finch-Savage, W.E. and Bassel, G.W. (2016). Seed vigour and crop establishment: Extending performance beyond adaptation. *J. Exp. Bot.* **67**(3): 567-591.
- Foodstruct. (2026). Comparative analysis: Edamame vs. mature soybeans. *Foodstruct Nutrition Database.* <https://foodstruct.com/compare/edamame-vs-soybean>.
- Gao, H., Wu, G., Wu, F., Zhou, X., Zhou, Y., Xu, K., Li, Y., Zhang, W., Zhao, K., Jing, Y. and Feng, C. (2024). Genome-wide association analysis of yield-related traits and candidate genes in vegetable soybean. *Plants.* **13**(11): 1442.
- Global Edamame Association. (2021). Market Overview and Growth Trends for Edamame: 2021 Industry Report. *Global Edamame Association.* <https://www.iea.org/reports/gas-market-report-q4-2021/main-findings>.
- Hosono, T., Katayama, K. and Hosokawa, H. (2010). Effect of mulching and row cover on soil temperature and the emergence of early direct-seeded edamame (*Glycine max*). *Bulletin of the National Agriculture Research Center.* **14**: 17-31.
- ICAR-Indian Institute of Soybean Research. (2022). Annual Report 2022. ICAR-IISR, Indore, Madhya Pradesh, India.
- Jha, P., Kumar, V., Rani, A. and Kumar, A. (2021). Mapping QTLs controlling the biosynthesis of maltose in soybean. *Rom. Biotechnol. Lett.* **26**(5): 2936-2941.
- Johnson, D.R. and Luedders, V.D. (1974). Effect of planted seed size on emergence and yield of soybeans [*Glycine max* (L.) Merr.]. *J. Agron.* **66**: 117-118.
- Kering, M.K. and Zhang, B. (2015). Effect of priming and seed size on germination and emergence of six food-type soybean varieties. *International Journal of Agronomy.* **1**: 1-6. <https://doi.org/10.1155/2015/859212>.
- Khan, F.A., Amir, M., Narayan, S., Dar, Z.M. and Khan, M.H. (2023). Vegetable soybean (Edamame): A potential area of research-A review. *SKUAST J. Res.* **25**(3): 376-386.
- Kim, S.H. and Lee, B.W. (2020). Recent advances in vegetable soybean research: Nutritional, functional and ecological importance. *J. Agron.* **112**(5): 4258-4268.
- Konovsky, J., Lumpkin, T.A. and Mc Clary, D. (1994). Edamame: The Vegetable Soybean. In: *Understanding the Japanese Food and Agrimarket: A Multifaceted Opportunity.* [A.D. O'Rourke (Ed.)], Food and Agricultural Products Marketing Policy Center, Washington State University. pp. 173-181.

- Kuchlan, M.K., Kuchlan, P. and Srivastava, M. (2023). Improvement in seed germination potential and adaptability of vegetable soybean (*Glycine max* Merr.). *J. Oilseeds Res.* **40**: 408-409.
- Kumar, V., Rani, A. and Chauhan, G.S. (2005). Quantitative and qualitative analysis of trypsin inhibitor during seed development in Indian soybean genotype. *J. Food Sci. Technol.* **42**: 477-480.
- Kumar, V., Rani, A. and Chauhan, G.S. (2010). Nutritional Value of Soybean. In: *The Soybean: Botany, Production and Uses*. [Singh, G. (Ed.)], CAB International. pp. 375-403.
- Lee, J., M. Renita, R.J. Fioritto, S.K. Martin, St., Schwartz, S.J. and Vonovotz, Y. (2004). Isoflavone characterization and antioxidant activity of Ohio soybeans. *J. Agrl. Food Chem.* **52**: 2647-2651.
- Li, X., Welbaum, G.E., Rideout, S.L., Singer, W. and Zhang, B. (2022). Vegetable Soybean and its Seedling Emergence in the United States. In: *Legume Research*. [B. Zhang (Ed.)]. IntechOpen. **1**: 1-18.
- Marimin, F.D., Martini, S., Astuti, R. and Suharjito, H.S. (2010). Added value and performance analyses of Edamame soybean supply chain: A case study. *Oper. Supply Chain. Manag.* **3**: 148-163.
- Masuda, R. (1991). Quality Requirement and Improvement of Vegetable Soybean. In: *Vegetable Soybean: Research Needs for Production and quality improvement* [S. Shanmugasundaram (Ed.)], AVRDC Publication No. 91-349. Asian Vegetable Research and Development Center. pp. 92-102.
- Masuda, R. (2004). Edamame: Soybean's Sweet Secret. *Soybean Genetics Newsletter*. **31**: 1-6.
- Mbuvi, D.M. and Litchfield, A.R. (1995). Secondary metabolites in vegetable soybeans: Role in plant defense and nutrition. *The Journal of Agricultural Science*. **125(2)**: 245-251.
- Messina, M. (2001). An Overview of the Health Effects of Soyfoods and Soybean Isoflavones. In: *Proceedings of the Second International Vegetable Soybean Conference*. [T.A. Lumpkin and S. Shanmugasundaram (Eds.)]. pp. 117-122.
- Mimura, M., Coyne, C.J., Bambuck, M.W. and Lumpkin, T.A. (2007). SSR diversity of vegetable soybean [*Glycine max* (L.) Merr.]. *Genet. Resour. Crop Evol.* **54**: 497-508.
- Ministry of Agriculture and Farmers Welfare. (2020). Annual Report 2020-21. Department of Agriculture, Cooperation and Farmers Welfare, Government of India, New Delhi.
- Mohamed-Yasseen, Y., Barringer, S.A., Splittstoesser, W.E. and Costanza, S. (1994). The role of seed coats in seed viability. *Bot. Rev.* **60**: 426-439.
- Nagalakshmi, S. and Prakash, J. (2015). Nutritional and functional characteristics of edamame (vegetable soybean): A review. *J. Food Sci. Technol.* **52(6)**: 2757-2767.
- Nair, R.M., Boddepalli, V.N., Yan, M.R., Kumar, V., Gill, B., Pan, R.S., Wang, C., Hartman, G.L., Silva, E., Souza, R. and Somta, P. (2023). Global status of vegetable soybean. *Plants*. **12(3)**: 609.
- Nair, R.M., Yan, M.R., Vemula, A.K., Rathore, A., van Zonneveld, M. and Schafleitner, R. (2023). Development of core collections in soybean on the basis of seed size. *Legume. Sci.* **5**: 158.
- Nangju, D. (1979). Seed characters and germination in soybean. *Exp. Agric.* **15**: 385-392.
- Noodén, L.D., Blakley, K.A. and Grzybowski, J.M. (1985). Control of seed coat thickness and permeability in soybean. *Plant Physiol.* **79**: 543-545.
- Patil, M.V. and Shewale, S.A. (2018). Prospects of vegetable soybean cultivation in India. *IJCMAS*. **7(1)**: 456-463.
- Paulitz, T.C., Anas, O. and Fernando, D.G. (1992). Biological control of Pythium damping off by seed treatment with *Pseudomonas putida*. *Biocontrol Sci. Technol.* **2(3)**: 193-201.
- Powell, A.A. (1986). Cell membranes and seed leachate conductivity in relation to the quality of seed for sowing. *J. Seed Sci.* **10**: 81-100.
- Purcell, L.C., Salmerón, M. and Ashlock, L.O. (2021). Soybean Growth and Development. In: *Arkansas Soybean Handbook*. Little Rock: University of Arkansas Cooperative Extension Service; <http://uaex.edu/publications/pdf/mp197/2013>.
- Ravishankar, M., Pan, R.S., Kaur, D.P., Giri, R.R., Anil Kumar, V., Rathore, A., Easdown, W. and Nair, R.M. (2016). Vegetable soybean: A crop with immense potential to improve human nutrition and diversify cropping systems in Eastern India-A review. *Soybean Research*. **14(2)**: 1-24.
- Rezapour, R., Kazemi-Arbat, H., Yarnia, M. and Zafarani-Moattar, P. (2013). Effect of seed size on germination and seed vigor of two soybean (*Glycine max* L.) cultivars. *IRJABS*. **43**: 396-401.
- Reznikov, S., Vellicce, G.R., González, V., de Lisi, V., Castagnaro, A.P. and Ploper, L.D. (2016). Evaluation of chemical and biological seed treatments to control charcoal rot of soybean. *J. Gen. Plant Pathol.* **82**: 273-280.
- Roland, J.P. (2011). Genistein activates human bitter taste receptors and contributes to the flavor of soy products. *J. Agric. Food Chem.* **59(18)**: 10016-10021.
- Sánchez, E., Kelley, K. and Butler, L. (2005). Edamame production as influenced by seedling emergence and plant population. *HortTechnol.* **15**: 672-676.
- Shanmugasundaram, S. (1991). The role of secondary metabolites in the flavor and marketability of vegetable soybeans. *Food Res. Int.* **24(6)**: 599-604.
- Shanmugasundaram, S., Nair, R.M., Yan, M.R. and Palada, M.C. (2015). Vegetable Soybean (Edamame). In: *Handbook of Vegetables*, Stadium Press, LLC. **3**: 521-555.
- Shelar, V.R., Shaikh, R.S. and Nikam, A.S. (2008). Soybean seed quality during storage: A review. *Agric. Rev.* **29**: 125-131.
- Sherif, M. (2013). Soybean, Nutrition and Health. In: *Soybean - Bio-active Compounds*. [H.A. El-Shemy (Ed.)], IntechOpen. pp. 153-174. <https://doi.org/10.5772/54545>.
- Shilpashree, N., Devi, S.N., Manjunathagowda, D.C., Muddappa, A., Abdelmohsen, S.A.M., Tamam, N., Elansary, H.O., El-Abedin, T.K.Z., Abdelbacki, A.M.M. and Janhavi, V. (2021). Morphological characterization, variability and diversity among vegetable soybean (*Glycine max* L.) genotypes. *Plants*. **10**: 671.
- Takahashi, Y. and Ohyama, T. (2011). Production and Consumption of Green Vegetable Soybeans "Edamame". *Soybeans: Cultivation, Uses and Nutrition*. pp. 427-443.

- Tsindi, A., Kawuki, R. and Tukamuhabwa, P. (2019). Adaptation and stability of vegetable soybean genotypes in Uganda. *Afr. Crop Sci. J.* **27(2)**: 267-280.
- University of California, Davis, Department of Nutrition. (2018). What is Soy? [Fact Sheet]. UC Davis Nutrition Information Research Center. [<https://nutrition.ucdavis.edu/outreach/nutr-info-sheets/soy>].
- USDA Foreign Agricultural Service (2024). Global Agricultural Information Network (GAIN) Reports.
- USDA Food Data Central. (2026) Nutrient profiles for Tofu (F004245), Tempeh (F016123) and Edamame (F011212).
- Wang, B., Bu, Y., Zhang, G., Liu, Na, Feng, Z. and Gong, Y. (2024). Comparative transcriptome analysis of vegetable soybean grain discloses genes essential for grain quality. *BMC Plant Biol.* **24(1)**: 491.
- Wang, Z., Yu, D., Morota, G., Dhakal, K., Singer, W., Lord, N., Huang, H., Chen, P., Mozzoni, L. and Li, S. (2023). Genome-wide association analysis of sucrose and alanine content in edamame. *Front. Plant Sci.* **3(13)**: 1086007.
- Williams, M.M. (2015). Phenomorphological characterization of vegetable soybean germplasm lines for commercial production. *Crop Sci.* **55**: 1274-1279.
- Williams, M.M. and Bradley, C.A. (2017). Fludioxonil + Mefenoxam seed treatment improves edamame seedling emergence. *HortTechnology.* **27(6)**: 846-851.
- Wszelaki, A.L., Delwiche, J.F., Walker, S.D., Liggett, R.E., Miller, S.A. and Kleinhenz, M.D. (2005). Consumer liking and descriptive analysis of six varieties of organically grown edamame-type soybean. *Food Qual. Prefer.* **16(8)**: 651-658.
- Xavier, A., Hall, B., Hearst, A.A., Cherkauer, K.A. and Rainey, K.M. (2017). Genetic architecture of phenomic-enabled canopy coverage in *Glycine max*. *Genetics.* **206(2)**: 1081-1089.
- Xiao, K., Kinkel, L.L. and Samac, D.A. (2002). Biological control of *Phytophthora* root rots on alfalfa and soybean with *Streptomyces*. *Biological Control.* **23(3)**: 285-295.
- Xue, A.G., Cober, E., Morrison, M.J., Voldeng, H.D. and Ma, B.L. (2007). Effect of seed treatments on emergence, yield and root rot severity of soybean. *Can. J. Plant Sci.* **87(1)**: 167-174.
- Yu, X., Fu, X., Yang, Q., Jin, H., Zhu, L. and Yuan, F. (2021). Genome-wide variation analysis of four vegetable soybean cultivars based on re-sequencing. *Plants.* **11(1)**: 28.
- Zeipina, S., Alsina, I. and Lepse, L. (2017). Insight in edamame yield and quality parameters: A review. *Res. Rural Dev.* **2**: 40-44.
- Zhang, G.W., Xu, S.C., Mao, W.H., Hu, Q.Z. and Gong, Y.M. (2013). Determination of the genetic diversity of vegetable soybean [*Glycine max* (L.) Merr.] using EST-SSR markers. *J. Zhejiang Univ. Sci. B.* **14(4)**: 279-288.
- Zhang, Q., Li, Y., Chin, K.L. and Qi, Y. (2017). Vegetable soybean: seed composition and production research. *Italian J. Agron.* **12(3)**: 872.
- Zhang, Q.Y., Hashemi, M., Hebert, S.J. and Li, Y.S. (2013). Different responses of pre emergence and early seedling growth to planting depth between vegetable soybean and grain soybeans. *Legume Research.* **36(6)**: 515-521.