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Possibility of Vegetable Soybean Cultivation in North Europe

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Abstract: The interest in cultivation of vegetable soybeans, also known as edamame, in the North Europe region has increased during the last years due to their high nutritional value and excellent taste properties. During the last decade the possible growing area for soybeans has expanded towards the north due to changes in climate as well as breeding efforts. In order to adopt vegetable soybean growing technology for commercial cultivation in the North Europe region, independent experiments were carried out in Latvia and Norway. This study shows that vegetable soybean is a crop with potential for successful cultivation at higher latitudes, such as the Nordic–Baltic region in North Europe, with yield levels comparable to other regions of the world. We observed that hydrothermal conditions had the most significant impact on soybean plant development. Sowing or planting as early as possible is a key to obtaining sufficient yield levels. In the study, the vegetation period needed to be at least 123 to 127 days, with growing degree days (GDD) at least 650, and hydrothermal coefficient (HTC) above 1. Under such conditions, the obtained marketable yield in Latvia ranged between 3 to 10 t ha^{-1} during the period of 2017–2019, and 1.2 to 10.5 t ha^{-1} in Norway. Planting density of 20–25 plants per m^2 appeared to be optimal. The variety 'Midori Giant' showed the most stable yield outcome, but 'Chiba Green' also gave a satisfactory yield.

Keywords: edamame; *Glycine max* L.; hydrothermal conditions; growing degree days

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1. Introduction

Vegetable soybean, also called edamame, is a soybean (*Glycine max* L. Merrill) type with larger seeds, good seed flavour and texture. Vegetable soybeans are harvested before full maturity, when pods are green and just before turning yellow, when the beans fill 80–90% of the pod (BBCH 77–79) [1,2]. Edamame was known first from China, as early as in the second century BC [3]. Also in Japan, vegetable soybean has been known for more than 400 years [4]. Nowadays, edamame is a popular food consumed in Asia and the United States [5]. During the last decade, the vegetable soybean was introduced into the diet also in the Baltic Sea region and Scandinavia. It is a valuable food due to its high protein, fat, phospholipids, phosphorus, calcium, iron, riboflavin, vitamin E, dietary fiber, and isoflavones content [5–7]. The content of calcium, phosphorus, and potassium in soybean is twice as high in comparison to green pea. In addition, the content of sodium, iron, and vitamins B1 and B2 are higher than in peas. Edamame contains a rather high level of vitamin C [3,8]. Clinical studies have shown that isoflavones in soybean reduce cholesterol level and, thus, reduce the risk of cardiovascular diseases, cancer, diabetes, osteoporosis, and menopausal symptoms [3,5]. The interest in possible cultivation of edamame plants in the North Europe region has been rising during the last years due to their high nutritional value and excellent taste properties.

Vegetable soybean is cultivated similar to grain soybean, but it is harvested at an earlier developmental stage [1]. Agronomical practices for grain soy cultivation may, therefore, be applicable also to vegetable soybean crops. According to the Food and Agriculture

Organization of the United Nations (FAO), for several decades, the growing region for soy excluded the Baltic States and Scandinavia [9]. However, during the last decade its growing area has expanded towards the north, due to climate change as well as plant breeding efforts. Therefore, soybean introduction has entered the applied research agenda in the North Europe region, aimed at expanding the boundary of its cultivation area in Europe [10].

Understanding the influence of the environment on the growth of a plant can assist in developing crop-management technology. Others state that temperature and soil moisture are the main factors ensuring yield formation for vegetable soybean [11]. Temperatures above 30 °C and below 13 °C negatively affect plant growth and yield development. The overall optimal temperature for vegetable soybean cultivation is around 25 °C. The optimal soil temperature for soybean sowing is at least 15 °C [12,13]. The referred amount of growing degree days (GDD) for vegetable soybean at physiological maturity range between 855 and 1125, depending on sowing time and variety [14].

Several publications point to soil moisture playing a crucial role for the soya plants, especially during the germination phase [12,15]. For good yield formation and good quality, 450–900 mm of precipitation or irrigation per season is recommended, depending on weather conditions, crop-management practices, and cycle timing [12,16]. More water is consumed in the flowering and pod-formation stages [12,17]. Flowering intensity, the number of pods, and plant height are strongly influenced by the soil moisture level. Also, plant morphological architecture and anatomical features can be influenced by water stress [18]. Very often in experiments, plant reaction to water stress depends on the genotype [19].

Thus, appropriate sowing time has a crucial influence on crop establishment and, consequently, yield. Besides, sowing time has influence on the balance between temperature and natural soil moisture [20,21]. It varies between geographical regions, depending on the climate and meteorological conditions of the particular year. To overcome natural weather conditions, several technological elements can be used to influence crop establishing and yield formation–planting of transplants vs. direct sowing in the field [22]; soil mulching vs. crop growing in the bare soil [13,22]; and using lower plant density in order to ensure higher penetration of solar radiation in the canopy and provide more soil resources (moisture and nutrition elements) per plant [21].

In order to prolong the vegetation period, thus ensuring longer period for accumulating GDD, transplants for crop establishing in the field, instead of direct sowing, is used [19]. This technological approach is suggested also to overcome the deficiency of soil moisture necessary for successful seed germination in the field and prolong the vegetation period in the regions where the vegetation period is rather short for crop development. This is important because delayed sowing results in shorter vegetation period and, thus, reduces marketable yield [23].

Mulching materials influence soil temperature, which can increase or reduce crop yield. Modification of crop microclimate by mulching the soil by dark mulching materials alters the soil temperature and affects plant growth and yield [11,13,24].

Vegetable soybean plants are more branched in comparison to grain soybean plants. Therefore, a lower density of plants promotes the development of sufficient leaf area and ensures adequate soil resources for plant development. It is also understood that lower plant density ensures darker pods [25]. The recommended distance between vegetable soybean rows is rather wide; it ranges between 0.4–0.9 m for row distance and 0.05–0.15 m between plants in a row [12,17].

In order to adopt vegetable soybean growing technology for commercial cultivation in the North Europe region, independent experiments were carried out in Latvia and Norway.

2. Materials and Methods

In Latvia, trials were carried out at the Institute of Horticulture (LatHort), located 90 km to the west from Riga (in Pūre) (57°37′ N, 22°921′ E, 57 m altitude), during three successive growing seasons, 2017–2019. Meteorological conditions during the investigation period (precipitation and average air temperature) were collected by an automatic meteorological station, 'Lufft', located at Pūre. The precipitation sum of the vegetation period for each year was 362.8, 171.9, and 369.8 mm, respectively. Dry beginning of the vegetation period, when seed germination, and intensive plant vegetative growth takes place, and were observed in all three trial years (Figure 1A). July was dry in 2017 and 2018, and August was extremely dry in 2017 and 2019. In September of 2017, excess precipitation was registered, and this influenced the total sum of precipitation per vegetation period. In comparison to long-term observations (period from 1986 to 2019), the vegetation periods of 2017 and 2018 could be characterized as extremely dry.

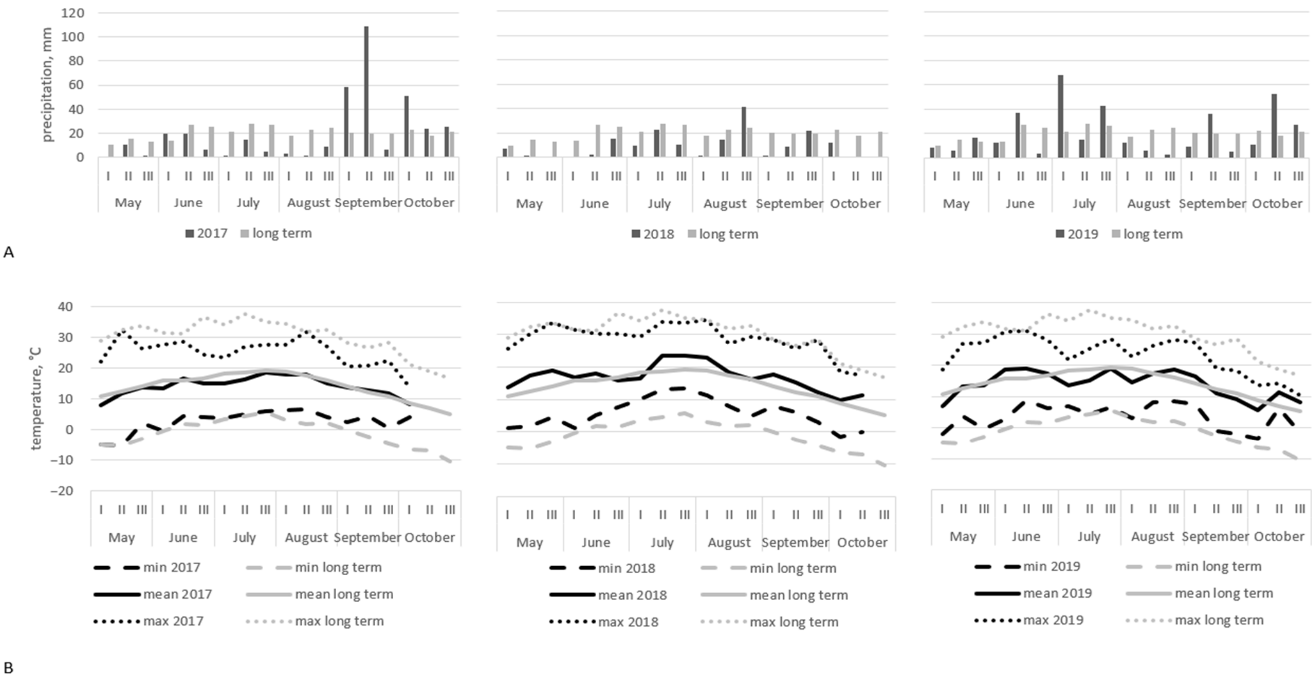

Figure 1. Meteorological data for the 2017–2019 growing seasons (per 10-day periods) and long-term observations (for 30-year period) in Latvia. (**A**)—precipitation, (**B**)—temperature.

The average monthly air temperature during 2017–2019 seasons were 6.2–17 °C, 10.0–21.1 °C, and 8.3–18.3 °C, respectively (Figure 1B). The air temperature of the 2018 season was the most adequate for vegetable soybean development from all trial years. 2017 was the coolest year, and average temperature was registered below the long-term observed in the most intensive soybean growth period—from May to August. In 2019, air temperature was fluctuating, with notable decrease in July, contrary to long-term data, when July is the warmest month of the season.

The balance of hydrothermal conditions in the trial is expressed by the hydrothermal coefficient (HTC). The driest year, according to the hydrothermal coefficient (HTC) in Latvia, was 2018 when no one month from May to September (except the end of August) had HTC exceeding 1—which indicated insufficient precipitation and too high a temperature during the intensive plant development and yield formation period. In 2017, the HTC from the end of June to August indicated insufficient hydrothermal conditions for soybean development. In 2019, HTC was below 1 only in June and August.

The soil type of the trial site was a sandy loam, characterized by pH_{KCl} 6.2, P_2O_5—224 mg kg^{-1}, K_2O—300 mg kg^{-1}, and organic matter of 3.5%.

In Norway, the trials were performed during the years 2018 and 2019 at the agricultural research station of NIBIO (Norwegian Institute of Bioeconomy) at Landvik, in Grimstad (58°34′ N, 8°52′ E, 6 m a.s.l.), on a loamy sand soil (10% silt, 3% clay, ~3.1% soil organic matter). Meteorological conditions during the investigation period (precipitation and average air temperature) were collected by an automatic meteorological station located at Landvik (https://lmt.nibio.no/, accessed on 15 May 2022). The meteorological weather station at Landvik is located within 100 m distance of both years' trial fields. The summer of 2018 was unusually warm and dry, with temperatures well exceeding normal (Figure 2). The HTC at the beginning of the vegetation period of 2018 in Landvik was fluctuating between 0 and 6.3, but on average for the whole vegetation period it was rather high—exceeding 2. This indicates good hydrothermal conditions for soybean plant development and yield formation. In 2019, the hydrothermal conditions were much better, in some periods even exceeding the optimum. However, during both seasons the trials were irrigated when needed, to avoid drought stress.

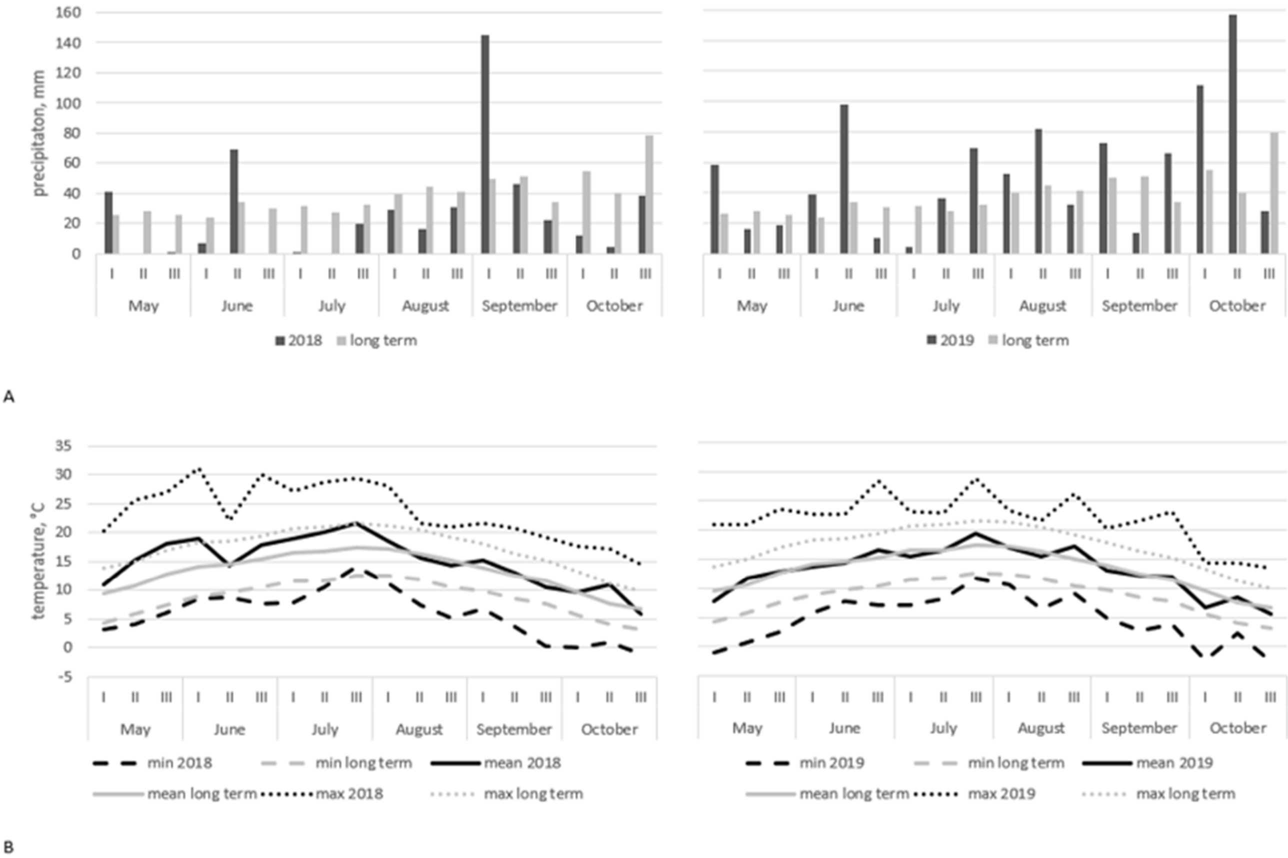

Figure 2. Meteorological data for the 2018–2019 growing seasons (per 10-day periods) and long-term observations for the 30-year period 1991–2020 in Norway. (**A**)—precipitation, (**B**)—temperature.

2.1. Experimental Design in Latvia

During three growing seasons (2017–2019) of the three-factorial experiment, four replicates were carried out in LatHort:

- factor A—variety ('Chiba Green'—A_1, 'Midori Giant'—A_2) (Wannamaker Seeds Inc., Saluda ews, NC, USA);
- factor B—growing method (direct sowing in the field—B_1, by transplanting the plants—B_2); and
- factor C—plant density (13 plants per m^2—C_1, 20 plants per m^2—C_2).

The growing season in 2017 started on 29 May, but in 2018 and 2019 it started only in June (26 and 7 June, respectively), when direct sowing in the field took place. Sowing depth was 1.5 cm. Seeds were inoculated with the *Bradyrhizobium japonicum* bacterium (HiStick®).

Seedlings for transplanting were grown in trays (volume 140 cm^3). Seedlings were planted in the field on 19 June, 1 June, and 22 May, respectively (Table 1).

Table 1. Vegetation period parameters (sowing, planting, and harvesting dates and GDD) for vegetable soybean grown in LatHort during 2017–2019. Base temperature 10 °C was used in GDD calculation.

	2017	**2018**	**2019**
	Field-sown plants		
Sown in the field	29 May	26 June	07 June
Harvest time	03.10.	18.10.	23–30.09.
Vegetation period	127 days	124 days	107–117 days
GDD	656	785	656
	Transplanted plants		
Planted in the field *	19 June	01 June	22 May
Harvest time	10.10.	04.09.	16–21.08.
Vegetation period **	123 days	95 days	88–93 days
GDD	751	1092	651

* 3 weeks before planting seedlings were grown in greenhouse. ** calculated from the day of planting in the field.

Sowing density variants in the present work were chosen based on the scientific literature studies on vegetable soybean cultivation, as well as on the observations obtained in the preliminary research developed in LatHort [12,17]. Depending on the plant density, soybean was grown in two-row or three-row beds, respectively, 0.35 and 0.70 m between rows within beds, and 0.10 m between plants in the row. During the growing period, plant fertilizer and chemical plant protection were not applied.

Plants sown directly in the field in 2017 were harvested 127 days after sowing (on 3 October). In 2018 and 2019 growing periods were shorter because sowing time was later due to the long period of low temperature in the spring. The yield was harvested 114 days after sowing (on 18 October) in 2018 and in 107–117 days after sowing (on 23 September–1 October) in 2019. The yield of plants grown from seedlings was harvested in 123 (on 10 October), 95 (on 5 September), and 90 (on 20 August) days after transplanting (Table 1).

Harvest was performed manually, when at least 80% of plants in the plot reached harvest maturity (BBCH 77–79). Only marketable pods were harvested.

Morphological traits, such as plant height, pod number per plant, and plant weight, were measured for 10 plants per plot at harvest. The total yield from each plot was measured and calculated to t ha^{-1}.

2.2. Experimental Design for Trials in Norway

In the Norwegian trials, fields were sown directly, using an Øyjord Horticultural Seed Drill, with a row distance of 0.5 m and plant density of 25 seeds m^{-2}. Sowing depth was 1.5 cm in 2018 and 3 cm in 2019. Seeds were inoculated with *Bradyrhizobium japonicum* directly prior to sowing, using peat-based Legumefix for soybean (Legumetechnology, Nottingham, UK). The cultivar used in the study was Midori Giant (Wannamaker Seeds Inc., Raleigh, NC, USA). Plot size was 6.4 m^2, and all treatments had three replications.

Soil temperature early in the growing season is one of the limiting factors for soybean cultivation at high latitudes. The trial in 2018 examined pre-plant mulching compared to no mulching, combined with three different sowing dates: 14 May, 23 May, and 1 June. In the mulching treatment, the soil was covered with a transparent polyethylene foil for one week prior to sowing, aiming to increase the soil temperature to aid faster and more uniform seed germination. The foil was removed at the day of sowing, and not reapplied. In 2019, a different approach was used. The whole trial was covered with fleece cloth after sowing, and the cover remained on the crop for four weeks after sowing.

Harvest and registration of traits were performed similarly to the Latvian trials. An area of 4.8 m^2 of each plot was harvested manually to record total and marketable yield, and the data was calculated to t ha^{-1}.

2.3. Growing Degree Days (GDD)

GDD were calculated to evaluate temperature conditions during the growing period of the vegetable soybean in our trials (Tables 1 and 2). GDD expresses the accumulation of heat during the growing period and is estimated by arithmetic summation of daily mean temperature above a base temperature and expressed as growing degree days.

The equation used is:

$$\text{GDD}_{\text{per}} = \sum\nolimits_n \left(\frac{T_{max} - T_{min}}{2} \right) - T_{base}$$

where, GDD_{per}—growing degree days for period, Σ_n—days per period, T_{max}, T_{min}—daily maximum and minimum air temperature, respectively, and T_{base}—the base temperature [26].

Based on previous findings we considered T_{base} as 10 °C for the soybean growing season [11].

Table 2. Vegetation period parameters (sowing and harvesting dates and growing degree days (GDD)) for vegetable soybean grown in Norway in 2018 and 2019. Base temperature 10 °C was used in GDD calculation.

Sowing time	14 May 2018	23 May 2018	1 June 2018	13 May 2019
		pre-mulching		
Harvest time	20 September 2018	1 October 2018	15 October 2018	xn.a.
Vegetation period	129 days	131 days	136 days	n.a.
GDD	927	888	835	n.a.
		no mulching		
Harvest time	14 September 2018	30 September 2018	12 October 2018	n.a.
Vegetation period	123 days	130 days	133 days	n.a.
GDD	909	888	824	n.a.
		post-mulching		
Harvest time	n.a.	n.a.	n.a.	15 September 2019
Vegetation period	n.a.	n.a.	n.a.	125 days
GDD	n.a.	n.a.	n.a.	669

2.4. Determination of the Hydrothermal Coefficient

For the description of the growing conditions, particularly the balance between moisture and temperature during the vegetation period, the hydrothermal coefficient (HTC) was assessed as the ratio between precipitation to 1/10 of the sum of active temperatures (mean day temperature of the days when it was above 10 °C) [27]. Thus, this parameter provided rational information on the correlation between the amount of precipitation in the period, when the average day temperature exceeded +10 °C, and the sum of temperature in degrees in the same period (Table 3). The HTC was calculated by applying the equation described by Selyaninov:

$$\text{HTC} = \frac{\sum x}{\sum t} \times 10$$

where, Σx and Σt—the sums of precipitation and temperatures in the period, when the temperature has been above 10 °C [26,28,29].

The performed irrigation was taken into account when calculating HTC for both seasons in Norway.

When HTC is from 1.0 to 2.0, humidity is sufficient; HTC > 2.0—immoderately humid; HTC < 1.0—insufficient humidity; HTC from 1.0 to 0.7 is assumed as dry period; and HTC from 0.7 to 0.4—very dry period.

Table 3. Hydrothermal conditions during the trial period in both trial locations.

Month	10-Days Period	Latvia 2017	Latvia 2018	Latvia 2019	Norway 2018	Norway 2019
May	I	0.2	0.6	3.7	6.3	38.3
	II	1.1	0.1	0.6	0	3.3
	III	0.1	0.0	1.2	1.6	1.6
June	I	1.6	0.0	0.7	0.4	2.9
	II	1.1	0.1	1.9	4.9	6.8
	III	0.4	1.0	0.2	0.9	0.6
July	I	0.1	0.6	5.0	0.9	0.3
	II	0.9	1.0	1.0	2.7	3.4
	III	0.2	0.4	2.2	1.8	3.2
August	I	0.1	0.1	0.9	1.6	3.1
	II	0.1	0.8	0.4	1.1	5.3
	III	0.5	2.3	0.1	1.9	1.7
September	I	4.6	0.1	0.6	9.6	5.6
	II	8.5	0.6	4.7	3.9	1.2
	III	0.7	2.7	1.1	3.2	8.8
October	I	n.a.	n.a.	n.a.	2.6	n.a.
	II	n.a.	n.a.	n.a.	0.6	n.a.
Average		1.3	0.7	1.6	2.2	5.5

2.5. Statistical Analysis

The data shown are the mean values. All data were subjected to analyses of variance (ANOVA). In LatHort, data were analysed by using STATISTICA (Dell Software, Round Rock, TX, USA) and the level of significance was set at $p < 0.05$. Duncan's multiple range test was used to assess the significance of the data, which is indicated in the graphs and tables. Data from the Norwegian trials were analyzed for variance using the GLM (General linear model) procedure and significant differences determined by Duncan's multiple range test in SAS statistical software, version 9.4.

3. Results

In Latvia, in 2017, vegetable soybean yields significantly differed between growing methods ($p = 0.000$) and varieties ($p = 0.002$), but between plant densities no significant difference ($p = 0.10$) (Table 4) was stated.

Table 4. Main statistical parameters in trials with two vegetable soybean cultivars grown in two growing technologies and in two plant densities in Latvia, 2017–2019. A: variety, B: growing method (transplanting vs. direct sowing), and C: planting density.

Factor	Degrees of Freedom	Yield 2017 Effect	2017 F Value	2017 *p*-Value	2018 Effect	2018 F Value	2018 *p*-Value	2019 Effect	2019 F Value	2019 *p*-Value
A	1	**	11.814	0.002	***	19.139	0.000	**	8.394	0.008
B	1	***	19.078	0.000	***	25.152	<0.000	***	36.905	<0.0008
C	1	N.s.	2.858	0.104	N.s.	3.421	0.077	N.s.	1.138	0.297
A×B	1	N.s.	1.323	0.261	N.s.	2.796	0.108	N.s.	0.034	0.855
B×C	1	*	5.277	0.031	N.s.	1.722	0.202	N.s.	0.209	0.651
A×C	1	N.s.	0.113	0.739	*	5.805	0.024	N.s.	0.724	0.403
A×B×C	1	N.s.	0.173	0.681	N.s.	0.034	0.856	N.s.	0.197	0.661

N.s., not significant; *** significant at $p < 0.001$, ** significant at $p < 0.01$, and * significant at $p < 0.05$, according to the analysis of variance.

Yields ranged from 6.5 to 10.4 t ha^{-1} depending on the variant (Figure 3). The highest yield was obtained in the variant 'Midori Giant' from transplants at highest plant density. The lowest yield (6.5 t ha^{-1}) was harvested from directly-sown plants at highest plant density for the variety 'Chiba Green'. For both varieties, a higher yield was observed if plants were grown from transplants in the field at higher planting density—10.4 t ha^{-1} for 'Midori Giant' and 8.4 t ha^{-1} for 'Chiba Green'. In both growing methods and plant density variants, the most productive variety was 'Midori Giant'.

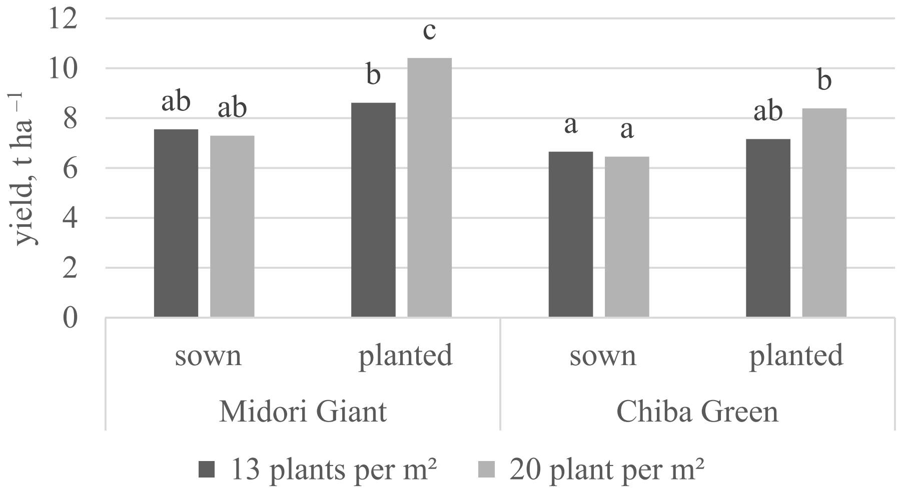

Figure 3. Vegetable soybean fresh pod yield in 2017, in Latvia. $n = 2$. Values marked by different letters have significant difference (Duncan's criteria, $p < 0.05$).

In 2018, similarly as in 2017, vegetable soybean yield was significantly influenced by the growing methods ($p = 0.000$) and varieties ($p = 0.002$), while there was no stated significant difference between plant densities ($p = 0.07$). That year's yield ranged between 3.9 and 8.6 t ha^{-1} (Figure 4). The highest yield was obtained from plants sown directly in the field at lower plant density for the variety 'Chiba Green'. The lowest yield was obtained from plants grown from seedlings at lowest plant density for the variety 'Midori Giant'. Contrary to both other years, in 2018 plants sown directly in the field yielded better than those transplanted, and lower plant density promoted yield formation. In 2018, the most productive variety was 'Chiba Green'.

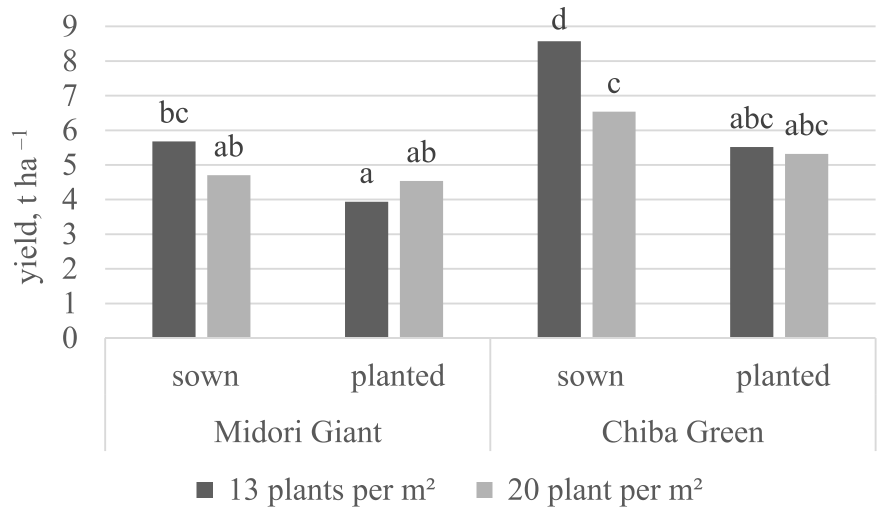

Figure 4. Vegetable soybean fresh pod yield in 2018, in Latvia. $n = 2$. Values marked by different letters have significant difference (Duncan's criteria, $p < 0.05$).

Also in 2019, vegetable soybean yields differed significantly between growing methods ($p = 0.000$) and varieties ($p = 0.007$), while no significant difference was stated between plant densities ($p = 0.30$). The yield ranged from 2.9 to 7.0 t ha^{-1} (Figure 5). Similarly to 2017, the highest yield was obtained for the variety 'Midori Giant' from transplants at the highest density. However, no significant difference was stated between plant densities in that year. The lowest yield was harvested in the variant with lower plant density for the field-sown plants of the variety 'Chiba Green'. Statistical analysis of the interaction of all factors did not show any significant interactions. As in 2017, also in 2019 the most productive variety was 'Midori Giant'.

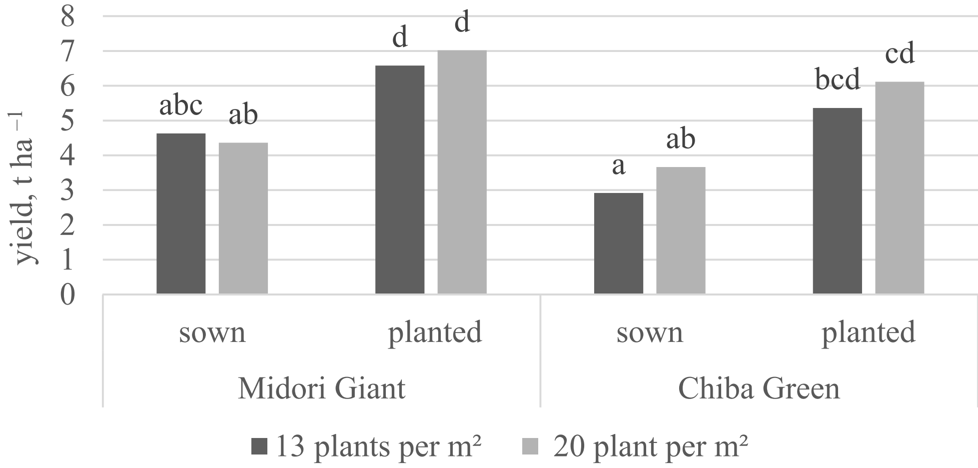

Figure 5. Vegetable soybean fresh pod yield in 2019, in Latvia. $n = 2$. Values marked by different letters have significant difference (Duncan's criteria, $p < 0.05$).

Statistical analysis of the results of all three years of the experiment showed that significant impact on the yield was found for year ($p = 0.000$) and growing method ($p = 0.000$), while for variety ($p = 0.31$) and planting density ($p = 0.54$) no significant effect was found. The results showed some significant interactions between factors: year × growing method ($p = 0.000$), year × variety ($p = 0.000$), and year × plant density ($p = 0.004$). These data indicate that very often no single factor influences yield, but it is determined by the interaction of several factors, although year has significant influence on all investigated factors.

The weather condition must be considered among the significant factors influencing the yield. HTC (hydrothermal coefficient) is suggested as an appropriate factor when calculating to evaluate moisture and temperature balance in a particular growing period [30]. The best vegetation season for vegetable soybean development was 2017, when spring conditions allowed planting on 29 May and ensured the longest vegetation period—127 days for the field-sown variant. Also, average HTC was 1.3 (Table 3) and its monthly fluctuations favoured good crop establishment. GDD (growing degree days) for the field-sown variant was only 656 and for transplanted variant it was also not very high—751. Nonetheless, those conditions favoured good yield formation for vegetable soybean. The driest and hottest year in Latvia was 2018. It had notable influence on the yield formation due to continuous insufficient precipitation and hot weather—average HTC was only 0.7 and it allayed possible positive influence of appropriate GDD, which was 785 for field-sown plants and 1092 for transplanted plants. Furthermore, due to the dry spring, the field-sown variant was established very late—only on 26.06. In 2019, HTC was below 1 only in June and August, and for all other months the hydrothermal balance was appropriate for plant growing. Nonetheless, the GDD was rather low, with 656 for the field-sown variant and 651 for the transplanted variant. Comparing HTC and GDD parameters, it seems that 2017 and 2019 were rather similar years, thus, it would be expected that yield should also be approximately at the same level. However, the average yield of 2019 was lower than in 2017. Concerning the length of the vegetation period, 2019 was the shortest of all trial years—107–117 days for the field-sown variant and 88–93 days for the transplanted plants. Contrary to 2017, when it was, correspondingly, 127 and 123 days. This could be the reason for the low yield in 2019.

Morphological parameters characterizing plant development were evaluated through all three seasons. The height of the plants varied, on average, from 0.50 to 0.77 m (Table 5).

Table 5. Morphological and productivity parameters for vegetable soybean in the period from 2017 to 2019.

Year	Variety	Growing Method	Plant Density, Plants m^{-2}	Plant Height, m	Pods Per Plant, pcs
2017	Midori Giant	direct sowing	13	0.70 ^{c*}	25 ^{c}
			20	0.68 ^{bc}	17 ^{b}
		planted transplants	13	0.63 ^{abc}	28 ^{c}
			20	0.56 ^{ab}	25 ^{c}
	Chiba Green	direct sowing	13	0.62 ^{abc}	20 ^{b}
			20	0.53 ^{a}	12 ^{a}
		planted transplants	13	0.56 ^{a}	24 ^{c}
			20	0.54 ^{a}	20 ^{b}
2018	Midori Giant	direct sowing	13	0.63 ^{cd}	28 ^{b}
			20	0.65 ^{d}	28 ^{b}
		Planted transplants	13	0.58 ^{bc}	26 ^{b}
			20	0.60 ^{bc}	27 ^{b}
	Chiba Green	direct sowing	13	0.61 ^{cd}	28 ^{b}
			20	0.56 ^{b}	27 ^{b}
		planted transplants	13	0.50 ^{a}	24 ^{b}
			20	0.51 ^{a}	19 ^{a}
2019	Midori Giant	direct sowing	13	0.77 ^{e}	34 ^{e}
			20	0.68 ^{d}	31 ^{d}
		planted transplants	13	0.57 ^{bc}	15 ^{ab}
			20	0.59 ^{bc}	16 ^{b}
	Chiba Green	direct sowing	13	0.62 ^{c}	31 ^{d}
			20	0.62 ^{c}	27 ^{c}
		planted transplants	13	0.54 ^{ab}	14 ^{a}
			20	0.50 ^{a}	14 ^{ab}

values marked by different letters have significant difference (Duncan's criteria, $p < 0.05$).

The overall tendency observed was that with higher plant density, plant height was lower, although this influence was not proved as statistically significant for all three years. Each year plant height significantly differed between varieties (p = 0.000) and growing method (p = 0.000). In all years the tallest plants were of the 'Midori Giant' variety (0.56–0.77 m). For 'Chiba Green' the height of plants ranged between 0.52 and 0.62 m. In direct-sowing variant, plants were taller (0.53 to 0.77 m) in comparison to transplanted plants (0.5 to 0.63 m). An average correlation was observed between plant height and the number of pods per plant (r = 0.59). Increasing the plant height increased the number of pods per plant. Statistically significant impact on pod number was found for all evaluated factors (p = 0.000) when the data of all tree years were evaluated together. However, if each year was evaluated separately, in the first and second year plant density had no significant effect on the number of pods per plant.

In the trial in Norway in 2018, sowing date strongly influenced total, as well as marketable yield (Table 6).

Table 6. Main statistical parameters for total and marketable yield in trials with vegetable soybean grown in two growing seasons, three sowing times, and two growing technologies in Norway, in 2018 and 2019. A: year, B: sowing time, and C: mulching treatment.

Factor	Degrees of Freedom	Total Yield 2018/2019			Marketable Yield 2018/2019		
		Effect	F Value	p-Value	Effect	F Value	p-Value
A	1	**	12.00	0.0038	**	13.90	0.0022
B	2	***	37.00	<0.0001	***	55.61	<0.0001
C	1	*	5.93	0.0288	*	6.68	0.0216
B×C	2	n.s.	0.57	0.5766	n.s.	0.93	0.41736

n.s., not significant; *** significant at $p < 0.001$, ** significant at $p < 0.01$, and * significant at $p < 0.05$, according to the analysis of variance.

With later sowing date, the yields got progressively lower. The latest sowing date had just 50%, or less, of the yield level at the earliest sowing date. The short mulching treatment prior to sowing in 2018 increased total yield slightly, while the effect was clearer for marketable yield (Figure 6). The results also showed that the fraction of total yield that is marketable decreased strongly with delayed sowing. The yield levels from the 2019 trial are included in Figure 6 for comparison, despite the different mulching treatment in this trial. Both total and marketable yield were at similar levels in both trial years, despite the different climatic conditions.

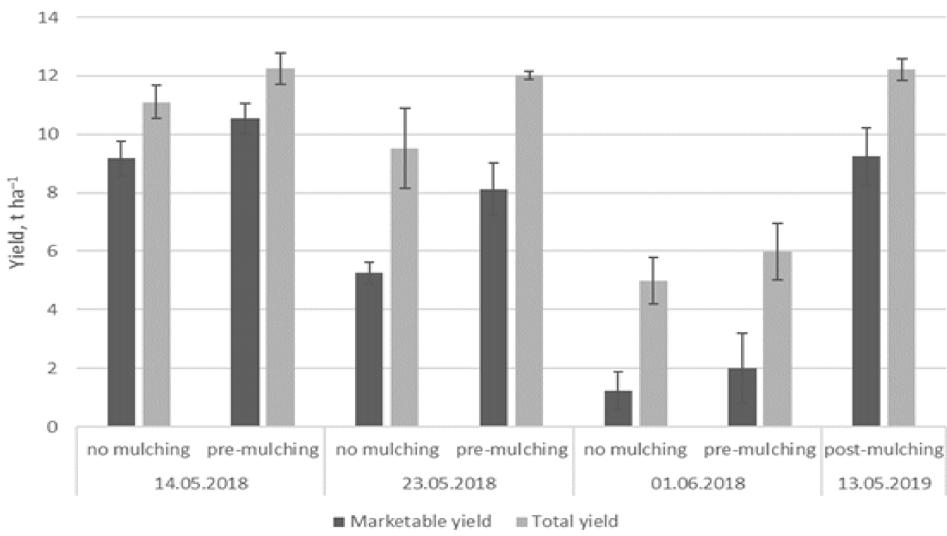

Figure 6. Marketable and total yield of vegetable soybean at three different sowing times, and with different soil mulching strategies in field trials in Norway in year 2018 and 2019. $n = 3$.

4. Discussion

Overall, the trials in this study achieved similar yields to elsewhere in the world. In experiments reported from the period 1994 to 1998, the yield varied from 2 to 10 t ha^{-1} in Colorado [31]. In an experiment in India, the yield of fresh pods of 10 vegetable soybean genotypes and varieties ranged from 6 to 11 t ha^{-1}, if the growing scheme was 0.3 m between rows and 0.1 m between plants in a row [6]. S. Mentreddy, with colleagues, found that in Taiwan, yield from Japanese varieties can be even 20 t ha^{-1}, from Chinese varieties 18 t ha^{-1} and from American varieties 16 t ha^{-1} [3]. An experiment in Brazil was conducted on five different genotypes that had been previously evaluated as the best. The plants were grown with 0.6 m between rows and 0.15 m between plants in the row, and the yield ranged from 6 to 11 t ha^{-1} [19]. Thus, we can conclude that it is possible to obtain comparable vegetable soybean yields in the North European agroecological conditions to elsewhere in the world. However, it should be considered, that a complex set of conditions has influence on the yield formation and its outcome.

The complex influence of agronomical and meteorological factors plays a crucial role in the yield formation of vegetable soybean [32]. According to our observations, the balance between temperature and moisture (hydrothermal conditions) has the most significant impact on soybean plant development. Also, in the experiments performed by others, similar observations were reported [18,33]. It should be stressed that all years of the trial in Latvia had insufficient precipitation through all of the growing season or for particular periods. Critical to production outcome is the moisture availability during the period from flowering to pod formation [30]. This can be assumed as a significant factor, influencing trial results. In the year 2018 in Latvia, GDD was the highest (785 and 1092 for field-sown and transplanted plants, correspondingly) and ensured an excellent temperature regime [11]. At the same time there was insufficient precipitation (160 mm per vegetation period), and, consequently, low average HTC for the year (0.7). Such conditions were not suitable for high yield formation. On the contrary, in the year 2017, when GDD was lower than optimal—656 in the field-sown variant and 751 for transplanted plants, and precipitation 263 mm, making average HTC 1.3—the highest yield was obtained in the period of our trial. Moreover, this was the year with the longest vegetation period—127 and

123 days for field-sown and transplanted plants. This suggests that the complex influence of hydrothermal conditions and length of the vegetation period determine the vegetable soya yield.

While sufficient temperature during the growing season has been considered a constraint for soybean production (vegetable, as well as mature soybeans) at higher latitudes than the current production areas, the most important limitation is probably sowing time, as demonstrated in our experiment in Norway in 2018. A delay of 9 or 18 days in sowing time strongly reduced the yield levels, and drastically reduced the marketable yield fraction. Delayed sowing reduced the length of the vegetation period, with less time to accumulate GDD. The strong reduction in marketable yield with delayed sowing also emphasizes that physical product quality (pod color, pod size, discoloration) is an important aspect to consider for vegetable soybean cultivation in marginal production areas. Soil mulching aiming to increase soil temperature at sowing time increased the yield levels, with the most pronounced effect at the earlier sowing dates. Sowing as soon as the soil temperature is sufficient for soybean germination, as well as agrotechnological methods to improve soil and/or air temperature in the plant's boundary layer, appear to be a prerequisite for successful vegetable soybean production [13] in the northern part of Europe under current climatic conditions. With the climate changes predicted in the near future, however, conditions for high-latitude vegetable soybean production most likely will be improved.

When evaluating the influence of concrete agrotechnological approaches on the yield outcome, we found that growing technology (field-sowing or transplanting), planting density, vegetation period, and mulching has influence on the yield.

In two out of three trial years transplanted plants gave higher yield in comparison to field-sown plants. Most probably, this was influenced by prolonged vegetation period and, thus, higher GDD. The lowest yield from transplanted plants was obtained in year 2018, when extreme drought was registered. Apparently, transplanting caused stress conditions for the plants, which was hard to overcome due to hot and dry weather. Even irrigation after transplanting was insufficient to help plants establish well. Obviously, transplanting shock had influence on plant development. Takahashi (2017) reported on an experiment with rice, which showed that transplanting shock constrained shoot growth. Injured roots cannot consume enough water [34], thus, water stress is the main cause of growth reduction due to transplanting shock [35]. Therefore, additional water stress caused by environmental factors results in reduced plant growth and, consequently, yield formation. Our study suggests that vegetable soybean cultivation using transplants can be considered as an appropriate technology under optimal hydrothermal conditions. In the case of continuous drought, repeated irrigation has to be applied after transplanting. Using transplants rather than direct sowing is likely to incur higher production costs, although this was not a factor in our study, and this should be taken into consideration by vegetable soybean farmers.

Insufficient moisture does not only influence plant yielding capacity, but also morphological parameters, such as pod filling and plant height. This has been observed in several experiments in different countries [18,30,36,37]. Both varieties included in our study ('Midori Giant' and 'Chiba Green') genetically have compact plants of 0.5 to 0.6 m in length, which corresponds, on average, to typical vegetable soybean plants. It is reported that the height of the soybean plant, depending on the variety, may vary between 0.4 and 1 m [17]. In India, the height of plants was found to range between 0.27 and 0.63 m [6]. The average plant height in our trials varied slightly between years, with the tallest plants in 2019 (on average 0.61 m), the most humid year among all three trial years, and the shortest plants (on average 0.58 m) in 2018, which was the driest year of the trial period.

The growing method influenced the plant's height. The longer plants in the Latvian trials developed if grown by direct sowing in the field (on average for all trial years 0.64 m) in comparison to transplanted plants (on average for all trial years 0.56 m). This can be explained by disrupted cytokinin/auxin balance by transplanting, which results in the increase of cytokinin concentration in the shoots, promoting shoot growth in the transplanted variant [38].

In our trial, taller plants (on average 0.61 m) were also observed in the higher density plantings, contrary to those grown at wider spacing (plant length was on average 0.58 m). Others are also reporting that plant length increases with increase of plant density up to a certain density, and then declines, depending on variety and season [39].

In our experiment, the number of pods per plant varied from 12 to 34 pods (Table 2). Similarly, a study in India found that the average number of pods per plant was 26 pods [6]. In another experiment performed in South Africa, under optimal moisture conditions, the number of pods on the plant ranged from 19 to 36. It is reported by Mangena, that drought stress significantly decreased the number of pods per plant [18], but this tendency was not observed in our experiment. In general, in our experiment, more pods were developed at the lowest plant density. The variety 'Midori Giant' showed a tendency to produce more pods per plant compared to the variety 'Chiba Green'. The influence of genotype on the pod number was reported by Dupong and Hatterman-Valenti [40] in North Dakota. They also found interactions between irrigation and meteorological conditions and the number of pods. In their trial, the pod number ranged between 28 and 81 [40]. In a Brazilian study, the number of pods varied with variety, ranging from 49 to 75 pods per plant [19].

5. Conclusions

Overall, our study has demonstrated that vegetable soybean is a crop with potential for successful commercial cultivation at higher latitudes, such as the Nordic–Baltic region in North Europe, with yield levels comparable to other regions of the world. Sowing or planting as early as possible is a key to sufficient yield levels.

According to our observations, the balance between temperature and moisture (hydrothermal conditions) has the most significant impact on the soybean plant development. In order to optimize vegetable soybean production, in our trials we found that vegetation period of 123 to 127 days, GDD at least 650, and HTC above 1 gave the most satisfactory yield outcome. Vegetation period can be prolonged by planting transplants on the field as soon as average air temperature exceeds 10 °C. After transplanting, intensive irrigation is needed to overcome transplanting stress. Soil mulching is an effective tool to increase yield outcome. Planting density 20 to 25 plants per m^2 is appropriate under optimal growing conditions. The vegetable soybean variety 'Midori Giant' showed the most stable yield outcome, but 'Chiba Green' also gave satisfactory yield.

Our results indicate that further research on the irrigation efficiency in vegetable soybean production in the region would be required.

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References

1. Moseley, D.; da Silva, M.P.; Mozzoni, L.; Orazaly, M.; Florez-Palacios, L.; Acuña, A.; Wu, C.; Chen, P. Effect of planting date and cultivar maturity in edamame quality and harvest window. *Front. Plant Sci.* **2021**, *11*, 585856. [CrossRef] [PubMed]
2. Meier, U. *Growth Stages of Mono-and Dicotyledonous Plants*; Julius Kühn-Institut (JKI): Quedlinburg, Germany, 2018; pp. 58–62.

3. Mentreddy, S.R.; Mohamed, A.I.; Joshee, N.; Yaav, A.K. Edamame: A nutritious vegetable crop. In *Trends in New Crops and New Uses*; ASHS Press: Alexandria, VA, USA, 2002; pp. 432–438.
4. Wszelaki, A.L.; Delwiche, J.F.; Walker, S.D.; Liggett, R.E.; Miller, S.A.; Kleinhenz, M.D. Consumer liking and descriptive analysis of six varieties of organically grown edamame-type soybean. *Food Qual. Prefer.* **2005**, *16*, 651–658. [CrossRef]
5. Battistini, C.; Gullon, B.; Ichimura, E.S.; Pereira Gomes, A.M.; Ribeiro, E.P.; Kunigk Leo Vieria Moreira, J.U.; Jurkiewicz, C. Development and characterization of an innovative symbiotic fermented beverage based on vegetable soybean. *Braz. J. Microbiol.* **2018**, *49*, 303–309. [CrossRef] [PubMed]
6. Basavaraja, G.T.; Naidu, G.K.; Salimath, P.M. Evaluation of vegetable soybean genotypes for yield and component traits. *Karnataka J. Agric. Sci.* **2005**, *18*, 27–31.
7. Hu, Q.; Zhang, M.; Mujumdar, A.S.; Xiao, G.; Jincai, S. Drying of edamame by hot air and vacuum microwave combination. *J. Food Eng.* **2006**, *77*, 977–982. [CrossRef]
8. Krinsky, B.F. The Development of a Lexicon for Frozen Vegetable Soybeans and Effect of Blanching Time on Sensory and Quality Parameters of Vegetable Soybeans during Frozen Storage. Master's Thesis, North Carolina State University, Raleigh, NC, USA, 2005.
9. Soybean production, 2018. Available online: https://ourworldindata.org/grapher/soybean-production (accessed on 15 May 2022).
10. Toleikiene, M.; Slepetys, J.; Sarunaite, L.; Lazauskas, S.; Deveikyte, I.; Kadziuliene, Z. Soybean development and productivity in response to organic management above the Northern Boundary of soybean distribution in Europe. *Agronomy* **2021**, *11*, 214. [CrossRef]
11. Kader Abdul, M. Effectiveness of Various Types of Mulching on Soil Moisture and Temperature Regimes under Rainfed Soybean Cultivation. PhD Dissertation, Kyoto University, Kyoto, Japan, 2020.
12. Dugje, I.Y.; Omoigui, L.O.; Ekeleme, F.; Bandyopadhyay, R.; Lava Kumar, P.; Kamara, A.Y. *Farmers' Guide to Soybean Production in Northern Nigeria*; International Institute of Tropical Agriculture: Ibadan, Nigeria, 2009; 23p.
13. Kader, M.A.; Senge, M.; Mojid, M.A.; Nakamura, K. Mulching type-induced soil moisture and temperature regimes and water use efficiency of soybean under rain-fed condition in central Japan. *Int. Soil Water Conserv. Res.* **2017**, *5*, 302–308. [CrossRef]
14. Kaushik, D.K.; Patel, S.R.; Chandrawanshi, S.K.; Khavse, R.; Chaudhary, J.L. Study on agrometeorological indices for soybean crop under different sowing dates in Chhattisgarh region of India. *Indian J. Agric. Res.* **2015**, *49*, 282–285. [CrossRef]
15. Zhang, Q.; Gao, Q.; Herbert, J.; Li, Y.; Hashemi, A.M. Influence of sowing date on phenological stages, seed growth and marketable yield of four vegetable soybean cultivars in north-eastern USA. *Afr. J. Agric. Res.* **2010**, *5*, 2556–2562.
16. Souza, G.M.; Catuchi, T.A.; Bertolli, S.C.; Soratto, R.P. Soybean under water deficit: Physiological and yield responses. In *A Comprehensive Survey of International Soybean Research—Genetics, Physiology, Agronomy and Nitrogen Relationships*; Board James, E., Ed.; IntechOpen: London, UK, 2012; pp. 273–298.
17. *Soya Beans Production Guideline*; Department of Agriculture, Forestry and Fisheries: Pretoria, South Africa, 2010.
18. Mangena, P. Water stress: Morphological and anatomical changes in soybean (*Glycine max* L). In *Plant, Abiotic Stress and Responses to Climate Change*; Andjelkovic, V., Ed.; IntechOpen: London, UK, 2018; pp. 9–31.
19. Castoldi, R.; Charlo, H.C.; Vargas, P.F.; Braz, L.T.; Carrão-Panizzi, M. Agronomic characteristics, isoflavone content and Kunitz trypsin inhibitor of vegetable soybean genotypes. *Hortic. Bras.* **2011**, *29*, 222–227. [CrossRef]
20. Mandić, V.; Đorđević, S.; Đorđević, N.; Bijelić, Z.; Krnjaja, V.; Petričević, M.; Brankov, M. Genotype and sowing time effects on soybean yield and quality. *Agriculture* **2020**, *10*, 502. [CrossRef]
21. Singh, M. Soybean Planting Considerations: Planting Date, Seeding Rate and Row Spacing Implications. Michigan State University Extension, Department of Plant, Soil and Microbial Sciences. 28 April 2022. Available online: https://www.canr.msu.edu/news/soybean-planting-considerations-planting-date-seeding-rate-and-row-spacing-implications (accessed on 15 May 2022).
22. Bec, S.; Pfeiffer, T.; Slone, D. Production System for Extending the Harvest Time Frame of Fresh-Market Edamame in Kentucky. Department of Plant and Soil Sciences and Department of Horticulture University of Kentucky. Available online: https://www.uky.edu/ccd/sites/www.uky.edu.ccd/files/edamame_extend_harvest.pdf (accessed on 15 May 2022).
23. Zhang, Q.; Li, Y.; Chin, L.K.; Qi, Y. Vegetable soybean: Seed composition and production research. *Ital. J. Agron.* **2017**, *12*, 1–20. [CrossRef]
24. Kader, M.A.; Senge, M.; Mojid, M.A.; Ito, K. Recent advances in mulching materials and methods for modifying soil environment. *Soil Tillage Res.* **2017**, *168*, 155–166. [CrossRef]
25. Kanovsky, J.; Lumpkin, T.A.; MeClary, D. Edamame: The vegetable soybean. In *Understanding the Japanese Food and Agrimarket: A Multifaceted Opportunity*; Haworth Press: Binghamton, NY, USA, 1994; pp. 173–181.
26. McMaster, G.S.; Wilhelm, W.W. Growing degree-days: One equation, two interpretations. *Agric. For. Meteorol.* **1997**, *87*, 291–300. [CrossRef]
27. Tchebakova, N.M. Evaluating the Agroclimatic Potential of Central Siberia. In *Novel Methods for Monitoring and Managing Land and Water Resources in Siberia*; Mueller, L., Sheudshen, A.K., Eulenstein, F., Eds.; Springer: Berlin/Heidelberg, Germany, 2015; pp. 287–305.
28. Evarte-Bundere, G.; Evarts-Bunders, P. Using of the hydrothermal coefficient (HTC) for interpretation of distribution of non-native tree species in Latvia on example of cultivated species of genus Tilia. *Acta Biol. Univ. Daugavp.* **2012**, *12*, 135–148.

29. Selyaninov, G.L. About the agricultural evaluation of the climate. *TrudyGGO* **1928**, *20*, 177–185.
30. Novikova Yu, L.; Bulakh, P.P.; Nekrasov Yu, A.; Seferova, I.V. Soybean response to weather and climate conditions in the Krasnodar and Primorye territories of Russia over the past decades. *Agronomy* **2020**, *10*, 1278. [CrossRef]
31. Johnson, D.; Wang, S.; Suzuki, A. Edamame: A vegetable soybean for Colorodo. In *Perspectives on New Crops and New Uses*; Janic, J., Ed.; ASHS Press: Alexandria, VA, USA, 1999; pp. 385–387.
32. Singh, M.; Siler, T. Soybean Planting Considerations for Maximum Profits. Michigan State University Extension, Department of Plant, Soil and Microbial Sciences. 21 April 2022. Available online: https://www.canr.msu.edu/news/soybean-planting-and-time-management-considerations (accessed on 15 May 2022).
33. Rahman, M.M.; Hosain, M.M. Plant density effects on growth, yield and yield components of two arrangement. *Asian J. Plant Sci.* **2011**, *10*, 278–286. [CrossRef]
34. Takahashi, N.; Sunohara, Y.; Fujiwara, M.; Matsumoto, H. Improved tolerance to transplanting injury and chilling stress in rice seedlings treated with orysastrobin. *Plant Physiol. Biochem.* **2017**, *113*, 161–167. [CrossRef]
35. Rietveld, J. Transplanting shock in bareroot conifer seedling. In *Webster's New Collegiate Dictionary*; G and C Merriam Co.: Springfield, MA, USA, 1959; pp. 49–71.
36. Gosa, S.C.; Lupo, Y.; Moshelion, M. Quantitative and comparative analysis of whole-plant performance for functional physiological traits phenotyping: New tools to support pre-breeding and plant stress physiology studies. *Plant Sci.* **2019**, *282*, 49–59. [CrossRef]
37. Sobko, O.; Stahl, A.; Hahn, V.; Zikeli, S.; Claupein, W.; Gruber, S. Environmental effects on soybean (*Glycine max* (L.) Merr) production in Central and South Germany. *Agronomy* **2020**, *10*, 1847. [CrossRef]
38. Kurepa, J.; Smalle, J.A. Auxin/cytokinin antagonistic control of the shoot/root growth ratio and its relevance for adaptation to drought and nutrient deficiency stresses. *Int. J. Mol. Sci.* **2022**, *23*, 1933. [CrossRef]
39. Xu, C.; Li, R.; Song, W.; Wu, T.; Sun, S.; Han, T.; Wu, C. High density and uniform plant distribution improve soybean yield by regulating population uniformity and canopy light interception. *Agronomy* **2021**, *11*, 1880. [CrossRef]
40. Dupong, L.M.; Hatterman-Valenti, H. Yield and quality of vegetable soybean cultivars for production in North Dakota. *HortTechnology* **2005**, *15*, 896–900. [CrossRef]