Role of nitrogen deficiency on growth and development near isogenic by E genes lines of soybean co-inoculated with nitrogen-fixing bacteria

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Nitrogen deficiency is a limiting factor in increasing efficiency of crop production in terrestrial ecosystems, and the transformation of inert nitrogen to forms that can be assimilated by plants is mediated by soil microorganisms. Symbiotic nitrogen-fixing bacteria and roots depend on each other and have developed various mechanisms for symbiotic coexistence. The aim of this work was to investigate the role of nitrogen deficiency on growth and development near isogenic by E genes lines of soybean (Glycine max (L.) Merr.): short-day (SD) line with genotype El2e3(E4e5E7), and photoperiodic insensitive (PPI) line with genotype e12e3(E4e5E7) grown from seeds inoculated with active strains of Bradyrhizobium japonicum against the background of local populations of diazotrophs of the genus Azotobacter spp. and establish how the soybean – Bradyrhizobium symbiosis will develop as the genes of both microsymbionts and macrosymbionts are responsible for the formation of the symbiotic complex. Plants were grown in a vegetation chamber, in sand culture. To assess the quantitative composition of microorganisms in the rhizosphere and rhizoplanes, 6 plants were selected from each soybean line, then separation of the zones of the rhizosphere and rhizoplanes was performed using the method of washing and the resulting suspension was used for inoculation on nutrient agar media (mannitol-yeast agar medium and Ashby medium). The results of study showed that seed inoculation and co-inoculation provides faster formation of the symbiotic soybean – Bradyrhizobium complex. Differences in nodulation rates between the short-day line with genotype El2e3(E4e5E7), and a photoperiodic insensitive line with genotype e12e3(E4e5E7) were identified. Determination of the amount of B. japonicum on the medium of mannitol-yeast agar in the rhizosphere and rhizoplane showed that inoculation by B. japonicum strain 634b caused a significant increase in the amount B. japonicum in the rhizosphere and rhizoplane in both soybean lines, comparison with non-inoculated seeds. Then, co-inoculation by B. japonicum strain 634b + Azotobacter chroococcum significantly increased the amount of B. japonicum only in the rhizoplane and decreased their number in the rhizosphere. Determination of the amount of A. chroococcum on the Ashby elective medium in the rhizosphere and rhizoplane showed that the inoculation by B. japonicum strain 634b caused a significant decrease in the amount of A. chroococcum both in the rhizosphere and in the rhizoplane of the PPI line of soybean, and in the rhizosphere the SD line, in comparison with non-inoculated seeds. That can testify to the competitive interaction of these microorganisms. However, the co-inoculation by B. japonicum strain 634b + A. chroococcum in the SD line significantly increased the number of A. chroococcum in the rhizoplane and decreased their number in the rhizosphere, in the PPI line their number decreased in the rhizoplane and increased in the rhizosphere, in comparison with non-inoculated seeds. Probably, the E genes (dominant or recessive state) of soybean isogenic lines affect the regulation of the content and distribution of sugars. It was established that the nitrogen deficiency stimulated development of the root system of plants and the synthesized sugars were distributed predominantly to the root system growth. We suppose that the seeds’ inoculation had extended sugar consumption to the symbiont, due to which it compensates the lack of nitrogen, but leads to a slower growth of the root system.

Keywords: Bradyrhizobium japonicum; Azotobacter chroococcum; Glycine max; isogenic lines; symbiosis; photoperiodic insensitive lines.

Introduction

Plants in the natural environment are surrounded by microorganisms, so they simultaneously interact with beneficial and pathogenic microflora. Today, one of the most important issues that need to be addressed is how plants control the interaction with beneficial microflora while at the same time inhibiting pathogenesis (Harris et al., 2020). In recent years, several studies have focused on the factors and mechanisms that regulate plant growth and development, as well as the functioning of signalling pathways (Ferguson & Mathesius, 2014) creating a complex communication and signalling network in plants which precisely controls interactions with microorganisms (Li et al., 2017). Many bacteria use membrane-diffusible small molecule quorum signals to coordinate gene transcription in response to changes in cell density, known as quorum sensing (QS) (Dong et al., 2020). Shi-Hui Dong recently reported the biochemical characterization of Bjl from Bradyrhizobium japonicum, which is involved in controlling the expression of virulence genes. In an open living system of interaction between a plant and microorganisms, plants provide the system with energy, while nitrogen fixing microorganisms provide plants with available forms of nitrogen. Many legumes can establish symbiotic relationships with specific soil bacteria collectively referred as rhizobia (Gano-Cohen et al., 2016), which possess the dinitrogenase enzyme complex capable of capturing atmospheric nitrogen (N2) and fixing it into ammonium, which is incorporated into carbon skeletons to form nitrogenous organic acids that can be readily assimilated by plants (Hungria et al., 2017). Although 78% of earth’s atmosphere consists of dinitrogen (N2), plants cannot utilize N2 for their growth. In fact, in an agro-ecosystem,
after water, N becomes the second most limiting factor for plant growth. Under natural conditions plants absorb nitrogen in the form of nitrates, ammonium released by prokaryotes capable of biological nitrogen fixation. However, it is not enough to meet the N demand in the intensely cultivated agro-ecosystem. Presently, to meet this demand industrial fertilizers are applied for plant growth. But leaching, volatilization and improper handling of the fertilizers lead to environmental pollution. Therefore, there is an urgent need to find an environmentally friendly strategy to reduce the application of chemical fertilizer and increase crop yield (Ferguson & Mathiesius, 2014; Nag et al., 2019). Plant-growth-promoting rhizobacteria of seeds with Azotobacter chroococcum strains can positively influence plant growth and reduce nitrogen fertilization (Melnykova et al., 2002; Wang et al., 2020). Finding out the patterns of plant-microbial interactions is one of the most important areas in modern biology. Knowledge about the biological essence of nitrogen-fixing symbiosis, and developing methods to increase its efficiency for use in agriculture will help to increase the productivity of cultivated plant varieties. The efficiency of the soybean – Bradyrhizobium symbiosis is increased, on the one hand, by the selection of modern varieties capable of active nodule formation, and on the other – by the selection of new strains (created by different methods) of nodule bacteria with high nitrogen-fixing activity (Kots et al., 2014; Aranjuelo et al., 2014).

Eight genes, which influence time from plant to first flower, have been identified in soybean Glycine max (L.) Merr. to date: E1 and E2, E3, E4, E5, E6, E7 and E8 (Cober et al., 2010). Two of these, E3 and E4 have been identified as phytochrome A genes while E2 has been identified as a GIGANTEA homolog and E1 as an inhibitor of FT. Alleles at these loci, in conjunction with photoperiod and temperature, regulate the timing of flowering and maturity of soybean lines. Soybean is a facultative short day plant, so under non-inductive long days (~14 h) and high temperatures (25–30 °C) dominant E alleles delay flowering, with the exception of the E6 locus. Lower temperatures reduced the delaying effect of E alleles under non-inductive photoperiods. Isolines with dominant E alleles at two or three loci flowered earlier under low temperature (18 °C) and non-inductive photoperiods compared to higher temperature (28 °C) with non-inductive photoperiods, but the time to flowering in both instances was still greater than the time to flower under inductive short photoperiods. This result underscored the importance of the E genes in the adaptation of soybean lines to specific climates and highlighted the requirement for a thorough understanding of their function in controlling flowering (Cober et al., 2014; Liu et al., 2017). It is known that soybeans are able to use the nitrogen supply in the seeds in the early stages of vegetative development, but after formation of the symbiotic apparatus, it begins to use biogenic nitrogen obtained from the symbiont (Vorobyev & Kots, 2018). The selection of the most effective pairs of nodule bacteria and a certain variety is increased, on the one hand, by the selection of modern varieties capable of active nodule formation, and on the other – by the selection of new strains (created by different methods) of nodule bacteria with high nitrogen-fixing activity (Kots et al., 2014; Aranjuelo et al., 2014).

In view of the above, the aim of our research is to study the role of nitrogen deficiency on growth and development near isogenic by E genes lines of soybean Glycine max (L.) Merr.: short-day (SD) line with genotype E1e2E3e5e7, and photoperiodic insensitive (PPI) line with genotype e1e2e3E4e5e7) grown from seeds inoculated with active strains of B. japonicum against the background of local populations of diazotrophs of the genus Azotobacter spp. and establish how the soybean – Bradyrhizobium symbiosis will be developing as the genes of both microsymbiont and macrosymbiont are responsible for the formation of the symbiotic complex (Runyanova, 2019).

Materials and methods

The objects of the study were near isogenic by E genes lines of soybean Glycine max (L.) Merr.; of the cultivar “Clark” with different combinations of alleles. In the dominant state, these genes cause a short-day response, and in the recessive state – photoperiodic insensitive. The studies used the short-day (SD) line with genotype E1e2E3e5e7, and photoperiodic insensitive (PPI) line with genotype e1e2e3E4e5e7, which were provided by the National Center for Plant Genetic Resources of Ukraine. Plants were grown in a vegetation chamber, in sand culture, in three litre pots. Prior to the commencement of the experiment, coarse sand was obtained from the river sand, washed thoroughly to remove sediments, dirt and dissolved salts and then autoclaved at 120 °C and pressure of 50 kPa. Each of four pots contained 10 plants.

The photoperiod was 16h of light and 8 h of dark and temperature of 20–24/17–20 °C (day/night). Humidity was maintained at 60–70% of the total moisture content of sand, watered with distilled water. Lighting from white fluorescent lamps, light intensity of 300 μmol photons m−² s−¹ (measured at just above the plant canopy). Inoculations was performed by B. japonicum (Kirchner) strain 634b, which was provided from the collection of cultures of nitrogen-fixing bacteria of the Department of Symbiotic Nitrogen Fixation of the Institute of Plant Physiology and Genetics of NASU. Co-inoculation was performed by A. chroococcum from the collection of microorganisms of the Department of Physiology and Biochemistry of Plants and Microorganisms of V. N. Karazin Kharkiv National University. The research scheme is presented in the diagram (Fig. 2).

Variants of the experiment: non-inoculated group – soybean seeds before sowing were sterilized with 70% ethanol for 15 min, washed under tap running water, inoculated group – soybean seeds before sowing were sterilized with 70% ethanol for 15 min, washed under running tap water and inoculated by aqueous suspensions of nodule bacteria B. japonicum strain 634b with a titer of 107 cells/mL (Turbidity Standard No. 5, Ukraine, 2014), co-inoculated group – soybean seeds before sowing were sterilized with 70% ethanol for 15 min, washed under running tap water and co-inoculation by B. japonicum strain 634b + A. chroococcum with a titer of 107 cells/mL (Turbidity Standard No. 5, Ukraine, 2014).

In order to restore physiological activity after storage in the conditions of the museum nodule bacteria were grown in biological tubes on the medium of mannitol-yeast agar (MDA), g/L: K2HPO4 (China, 2015) – 0.5, MgSO4·7H2O (China, 2015) – 0.2, NaCl (Ukraine, 2017) – 0.1, mannitol (Ukraine, 2016) – 10.0, yeast extract – 0.5, agar (Spain, 2017) – 15.0, distilled water, pH 6.8–7.0 (MT, Russia, 2016) for 7–8 days at 28 °C. To prepare aqueous suspensions of nodule bacteria in the sterile conditions of a laminar box (Technogen, Ukraine, 2019) from the surface of agar mannitol-yeast medium was taken one microbiological loop of bacterial biomass, placed in a test tube with sterile water (5 mL), and suspended Vortex (Bosson, Latvia, 2016) until homogeneous in the same consistency. Soybean seeds were inoculated with aqueous suspensions of nodule bacteria with a titer of 107 cells/mL. B. japonicum strain 634b was grown in mannitol-yeast agar medium (MDA), and A. chroococcum were grown in Asbyh medium (g/L: K2HPO4 (China, 2015) – 0.5, MgSO4·7H2O (China, 2015) – 0.2, NaCl (Ukraine, 2017) – 0.1, mannitol (Ukraine, 2016) – 10.0, K2SO4 (Ukraine, 2016) – 0.1, CaCO3 (Ukraine, 2014) – 5.0, agar (Spain, 2017), both at 28 °C, thermostat (Medaparat, Ukraine, 2018) (full growth reached at seven days).

The following morphometric parameters were measured: shoot and root weight, and number and weight of nodules on plant roots. The plants were carefully removed from the pots, the subterranean and terrestrial parts were separated, the root system was washed, the nodules were separated and measurements were taken.

The contents of carbohydrates and total nitrogen content were measured in fixed (120 °C for 30 min) dry leaves of middle tier from 3–5 plants. Total nitrogen content in fixed leaves was performed by the Kjeldahl method (Yermakov et al., 1987). The content of soluble sugars was determined by the Shvetsov and Luk’yanenko micromethod (Yermakov et al., 1987). Starch content in leaves determined by the Yastrembovich method (Yermakov et al., 1987). Samples for analysis were taken during daylight hours at 9 am and noon during flowering phase.

Evaluation of the activity of the functioning of the symbiosis soybean – Bradyrhizobium. To assess the activity of the symbiosis soybean – Bradyrhizobium we studied the root systems of plants. Each plant was carefully removed from the soil, the remnants of the substrate washed away, and then we counted the number of nodules, which is a sign of the activity of this symbiosis.
Fig. 1. General view of the vegetation experiment: near isogenic by E genes lines of soybean (Glycine max (L.) Merr.) in the early flowering phase

Fig. 2. The scheme of the research

Photoperiodic insensitive PI (e1e2e3E4e5E7) line

Sterilization of seeds with 70% ethanol

Group I
Non-inoculation
Control
Bradyrhizobium japonicum 634b
Determination of morphometric parameters (shoot and root weight, count the number of nodules on plant roots)

Group II
Inoculation of seeds
Bradyrhizobium japonicum 634b and Azotobacter chroococcum
Fixation of leaves for biochemistry analysis (determination of the carbohydrates and total nitrogen)

Group III
Co-inoculation of seeds
Bradyrhizobium japonicum 634b

Group IV
Non-inoculation
Control

Group V
Inoculation of seeds
Bradyrhizobium japonicum 634b and Azotobacter chroococcum
Determination of the number of microorganisms in the rhizosphere and rhizoplane

Group VI
Co-inoculation of seeds

The plants grew in a vegetation chamber, in sand culture for 4 weeks

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Determination of the number of microorganisms in the rhizosphere and rhizoplane. To assess the quantitative composition of microorganisms in the rhizosphere, 6 plants were selected from each soybean line. Separation of the zones of the rhizosphere and rhizoplane was performed using the method of washing. To do this, the roots with soil particles were placed in 100 mL of sterile water, stirred for several minutes and carefully removed with tweezers. The roots were then transferred to 100 mL flasks with sterile water and stirred for 40 minutes; soil that was washed from the roots was used to identify microorganisms in the rhizosphere. The resulting suspension was used for inoculation on dense nutrient media: MDA and Ashby. Their sterilization performed according to the following scheme: pipette 0.1 mL of the dilution suspension onto the surface of the solidified dried medium with a pipette and distributed over the agar using a glass spatula. The experiment was performed in triplicate. The seeded Petri dishes were incubated in a thermostat (Medical equipment, Russia, 2006) at 180 °C for 3 hours. Sowing was performed in an autoclave (Medical equipment, Russia, 2017) for 32.0% compared to the control variant of the experiment (Table 1). Co-inoculation by B. japonicum and A. chroococcum significantly reduces the mass of the root system in the PPI line by an average of 29.9% compared to the non-inoculated variant of the experiment and in the SD-line plants there was only a tendency to decrease in the mass of the root system compared to the control. There was no significant difference in the shoot biomass during flowering (Table 1).

The inoculation of seeds under conditions of nitrogen deficiency significantly reduces the mass of the root system in the PPI line by an average of 34.1% and in the SD-line plants by an average of 32.0% compared to the control variant of the experiment (Table 1). Co-inoculation with B. japonicum and A. chroococcum significantly reduces the mass of the root system in the PPI line by an average of 29.9% compared to the non-inoculated variant of the experiment and in the SD-line plants there was only a tendency to decrease in the mass of the root system compared to the control. There was no significant difference in the shoot biomass during flowering (Table 1).

The virulence of the studied rhizobia was determined by the number of initiated nodules of different sizes (Table 1). It was established that the inoculation of seeds under conditions of nitrogen deficiency significantly reduced nodule number per plant in both variants of the experiment with inoculation and with co-inoculation by 42.5% and 43.0%, respectively compared to the control (non-inoculated) variant of the experiment, but their nodule average weight was over 36.4% more than in control (Table 1).

The inoculation of seeds under conditions of nitrogen deficiency significantly increased nodule number per plant, inoculated by B. japonicum strain 634b in the control variant of the experiment and by 67.5% compared to the co-inoculation variant of the experiment. Furthermore, the average weight of nodules per plant in the SD soybean line was significantly higher in the variant with inoculation by B. japonicum strain 634b by an average of 28.3% compared to the control variant of the experiment and 42.0% compared to the co-inoculation variant of the experiment. Co-inoculation with B. japonicum and A. chroococcum caused reduction in the number of nodules in the SD soybean line roots, but nodule average weight was higher than in other variants in our experiment (Table 1).

The plant root system is crucial for anchorage and nutrition, and has a major role in plant adaptation, as well as in interactions with soil microorganisms. Figure 3 shows the formation of nodules under conditions of nitrogen deficiency on soybean roots depending on the variant of inoculation and the photoperiodic reaction of the soybean line, in the early flowering phase. Nodules were formed in all variants of experiment (Fig. 3). And they were situated in different part of the root system. In both soybean lines, on the roots of plants which were grown from non-inoculated seeds, single small nodules were situated only on the lateral roots (Fig. 3a, d).

The data were statistically analysed using Statistica 7.0 software (StatSoft Inc., USA). We calculated standard mean values (x) and standard deviation (SD). Differences between groups were determined using Tukey’s test, where the differences were considered reliable at P < 0.05 (with taking into account Bonferroni correction).

Results

It was established that the inoculation of seeds under conditions of nitrogen deficiency significantly reduces the mass of the root system in the PPI line by an average of 34.1% and in the SD-line plants by an average of 32.0% compared to the control variant of the experiment (Table 1). Co-inoculation by B. japonicum and A. chroococcum significantly reduces the mass of the root system in the PPI line by an average of 29.9% compared to the non-inoculated variant of the experiment and in the SD-line plants there was only a tendency to decrease in the mass of the root system compared to the control. There was no significant difference in the shoot biomass during flowering (Table 1).

Table 1

| Isolates of soybean | Treatment | Shoot biomass, g/plant | Root biomass, g/plant | Nodule number, n/plant | Nodule weight, g | Nodule average weight, g |
|---------------------|-----------|------------------------|-----------------------|------------------------|-----------------|--------------------------|
| Photoperiodic insensitive (PPI) line | Non-inoculated | 1.49 ± 0.27a | 2.08 ± 0.54bc | 19.14 ± 4.08bc | 0.213 ± 0.033bc | 0.011 ± 0.0006bc |
| | Inoculated with B. japonicum | 1.43 ± 0.32a | 1.37 ± 0.26b | 11.00 ± 3.46bc | 0.168 ± 0.018ab | 0.015 ± 0.0014ab |
| | Co-inoculated with B. japonicum + A. chroococcum | 1.29 ± 0.45c | 1.52 ± 0.13a | 10.91 ± 2.46bc | 0.163 ± 0.027ab | 0.015 ± 0.0013ab |
| Short-day (SD) line | Non-inoculated | 1.27 ± 0.15b | 1.81 ± 0.46bc | 8.91 ± 1.22ab | 0.145 ± 0.018ab | 0.016 ± 0.0015ab |
| Etcz3 (E4E5E7) | Inoculated with B. japonicum | 1.29 ± 0.24c | 1.23 ± 0.28ab | 12.33 ± 1.74ab | 0.186 ± 0.036ab | 0.015 ± 0.0012ab |
| | Co-inoculated with B. japonicum + A. chroococcum | 1.36 ± 0.38c | 1.61 ± 0.42c | 7.36 ± 2.29ab | 0.131 ± 0.013ab | 0.018 ± 0.0024ab |

Note: comparisons were made within the isogenic line of soybean, means in each column followed by different letters are not significantly different one from another on the results of comparison using the Tukey test (P < 0.05) with Bonferroni correction.

Fig. 3. The formation of nodules on soybean roots under nitrogen-limiting conditions depending on the variant of inoculation and the photoperiodic reaction of near isogenic by E genes lines of soybean (Glycine max (L.) Merr.) in the early flowering phase: a – photoperiodic insensitive line, non-inoculated group; b – photoperiodic insensitive line, single inoculation with B. japonicum strain 634b; c – photoperiodic insensitive line, co-inoculated with B. japonicum + A. chroococcum; d – short-day line, non-inoculated group; e – short-day line, single inoculation with B. japonicum strain 634b; f – short-day line, co-inoculated with B. japonicum + A. chroococcum
Table 2
Days from sowing to flowering, oligosaccharides, starch and total nitrogen content during flowering in leaves of near isogenic by E genes lines of soybean (Glycine max (L.) Merr.) under nitrogen-limiting conditions in response to seed inoculation consisting of single inoculation with B. japonicum strain 634b, or of co-inoculation with B. japonicum and A. chroococcum (x ± SD, n = 6)

| Isolines of soybean                      | Treatment            | Days from sowing to flowering | Oligosaccharides content in leaves, mg/g dry weight | Starch content in leaves, mg/g dry weight | Total N content in leaves, mg/g dry weight |
|-----------------------------------------|----------------------|------------------------------|-----------------------------------------------------|------------------------------------------|--------------------------------------------|
| Photoperiodic insensitive (PP) line     | Non-inoculated       | 32 ± 2                       | 11.6 ± 2.06                                         | 16.4 ± 2.19                              | 13 ± 0.06                                  |
|                                         | Inoculated with B. japonicum | 35 ± 3                      | 23.3 ± 2.76                                         | 16.5 ± 0.52                              | 15.5 ± 0.55                                |
|                                         | Co-inoculated with B. japonicum + A. chroococcum | 35 ± 2                      | 17.2 ± 0.56                                         | 10.0 ± 0.96                              | 14.0 ± 0.55                                |
| Short-day (SD) line                     | Non-inoculated       | 34 ± 11                      | 20.0 ± 0.56                                         | 24.7 ± 1.46                              | 14.4 ± 1.45                                |
|                                         | Inoculated with B. japonicum | 38 ± 20                     | 9.0 ± 0.48                                          | 11.7 ± 0.76                              | 9.2 ± 2.26                                 |
|                                         | Co-inoculated with B. japonicum + A. chroococcum | 38 ± 20                     | 17.0 ± 1.26                                         | 16.0 ± 0.68                              | 8.0 ± 0.90                                 |

Note: comparisons were made within the isogenic line of soybean, means in each column followed by different letters are not significantly different one from another on the results of comparison using the Tukey test (P < 0.05) with Bonferroni correction.

Single inoculation with B. japonicum strain 634b caused formation of big nodules located mainly on the main root, usually closer to its basal part (Fig. 3b, e). Co-inoculation with B. japonicum strain 634b + A. chroococcum caused formation of big nodules located mainly on the main root, their number was less than in the variant with a single inoculation (Fig. 3c, f). Co-inoculation slightly reduced the efficiency of the formation of the symbiotic apparatus, and stimulated the growth of the root system.

Table 2 shows that the effect of nitrogen deficiency reduced the number of days from sowing to flowering in both soybean lines by 3–5 days compared to plants grown from bacterized seeds.

The plants of the PPI line bloom earlier than SD line in the conditions of inoculation, compared with the control and 47.1–26.9% compared to the co-inoculation variant of the experiment. In SD plants of soybean line under conditions of inoculation with B. japonicum, the content of oligosaccharides decreased by 55.0–52.3% compared to the control and 35.5–65.0% compared to the co-inoculation variant of the experiment. In SD plants of soybean line under conditions of inoculation with B. japonicum, the content of oligosaccharides decreased by 55.0–52.3% compared to the control and 47.1–26.9% compared to the co-inoculation variant of the experiment. Also starch content in leaves of plants of the PPI was significantly lower (by 28.2%) at 8 am – 45.0% at noon) under conditions of inoculation, compared with the control and significantly increased by 72.2% (at noon) compared to the co-inoculation variant of the experiment. Total N content in leaves significantly increased only in the variant with a single inoculation (Table 2).

Despite the presence of nodules in non-inoculated plants of the experiment, the leaves of the lower tier visually showed pronounced signs of nitrogen deficiency, in inoculated and co-inoculated plants there were no signs of nitrogen deficiency (Fig. 4).

Figure 5 shows influence of complex seed bacterization on the number of nitrogen-fixing bacteria in the rhizosphere and rhizoplane. Figure 5a shows that single inoculation seeds by B. japonicum strain 634b significantly increased the number of B. japonicum in the rhizosphere (on average by 174.5%) and rhizoplane (on average by 121.0%) in the photoperiodical insensitive soybean line. Seed co-inoculation increased the number of B. japonicum in the rhizosphere (by an average of 189.2%), but reduced the content of B. japonicum in the rhizoplane by 20.4% compared to the number of microorganisms in the control. Seed inoculation increased the number of B. japonicum in the rhizosphere (by an average of 177.7%) compared to the number of microorganisms in the co-inoculation variant of the experiment (Fig. 5a).

Single inoculation seeds by B. japonicum strain 634b significantly increased the number of B. japonicum in the rhizoplane (on average by
but the supply of N to plants can be increased by using biological N\textsubscript{2} fixation as a limiting factor in many places of the world, demanding heavy fertilization, means to improve plant nutrition (Zhang et al., 2015). N deficiency is a natural landscape, and make the area already claimed by agricultural practices more productive (O’Callaghan, 2016; Fagorzi et al., 2021).

Fertilization has long been known to increase efficiency in agriculture, as a guarantee output and food supply, but cause the least, if any, alterations in the volume affected by roots – the rhizosphere – is one of the most important microbial hotspots determining the processes, dynamics and cycling of carbon (C), nutrients and water in terrestrial ecosystems. Rhizosphere visualization is necessary to understand, localize and quantify the ongoing processes and functions, but quantitative conclusions are very uncertain because of: (1) the continuum of the parameters between the root surface and root-free soil, i.e., there are no sharp borders, (2) differences in the distributions of various parameters (C, nutrients, pH, enzyme and microbial activities, gases, water etc.) across and along roots, (3) temporal changes of the parameters and processes with root growth as well as with water and C flows (Kuzyakov & Razavi, 2019). Furthermore, Moreau suggested that studying plants from N-poor habitats may assist in better understanding of plant traits directly controlling N-cycling microorganisms. Indeed, if we are to transition from high-input systems to low-input systems and exploit microbial properties that might be valuable in low-input sustainable systems, we need more information about those systems – not just conventional agricultural systems where large amounts of mineral

The increasing world population and the awareness of potential impacts of human activities on global weather changes demand that agriculture becomes more efficient. Technologies must be developed that guarantee output and food supply, but cause the least, if any, alterations in the volume affected by roots – the rhizosphere – is one of the most important microbial hotspots determining the processes, dynamics and cycling of carbon (C), nutrients and water in terrestrial ecosystems. Rhizosphere visualization is necessary to understand, localize and quantify the ongoing processes and functions, but quantitative conclusions are very uncertain because of: (1) the continuum of the parameters between the root surface and root-free soil, i.e., there are no sharp borders, (2) differences in the distributions of various parameters (C, nutrients, pH, enzyme and microbial activities, gases, water etc.) across and along roots, (3) temporal changes of the parameters and processes with root growth as well as with water and C flows (Kuzyakov & Razavi, 2019). Furthermore, Moreau suggested that studying plants from N-poor habitats may assist in better understanding of plant traits directly controlling N-cycling microorganisms. Indeed, if we are to transition from high-input systems to low-input systems and exploit microbial properties that might be valuable in low-input sustainable systems, we need more information about those systems – not just conventional agricultural systems where large amounts of mineral

Seed co-inoculation significantly increased the number of A. chroococcum in the rhizoplane (on average by 263.5%), but significantly reduced the content of A. chroococcum in the rhizosphere (on average by 52.0%) in the short-day soybean line compared to the number of microorganisms in the control (Fig. 6b). Seed inoculation by B. japonicum strain 634b significantly reduced the number of A. chroococcum in the rhizosphere (by an average of 60.5%) in the photoperiod insensitive soybean line compared to the number of microorganisms in the co-inoculation variant of the experiment (Fig. 6a).

Discussion

The increasing world population and the awareness of potential impacts of human activities on global weather changes demand that agriculture becomes more efficient. Technologies must be developed that guarantee output and food supply, but cause the least, if any, alterations in the volume affected by roots – the rhizosphere – is one of the most important microbial hotspots determining the processes, dynamics and cycling of carbon (C), nutrients and water in terrestrial ecosystems. Rhizosphere visualization is necessary to understand, localize and quantify the ongoing processes and functions, but quantitative conclusions are very uncertain because of: (1) the continuum of the parameters between the root surface and root-free soil, i.e., there are no sharp borders, (2) differences in the distributions of various parameters (C, nutrients, pH, enzyme and microbial activities, gases, water etc.) across and along roots, (3) temporal changes of the parameters and processes with root growth as well as with water and C flows (Kuzyakov & Razavi, 2019). Furthermore, Moreau suggested that studying plants from N-poor habitats may assist in better understanding of plant traits directly controlling N-cycling microorganisms. Indeed, if we are to transition from high-input systems to low-input systems and exploit microbial properties that might be valuable in low-input sustainable systems, we need more information about those systems – not just conventional agricultural systems where large amounts of mineral
N inputs are commonly used. In addition, significant work is still required to better understand the spatial and temporal dynamics of N turnover and root N uptake in the rhizosphere and its association with plant traits (Moraéu et al., 2019). The results of our studies show that the inoculation of seeds, under conditions of nitrogen deficiency, provides faster formation of the symbiotic soybean-B. japonicum complex. This fact is known and shown by many studies (Melnykova et al., 2002; Kots et al., 2011; Ohyama et al., 2017) and is widely used when recommending the joint use of inoculants and the use of reduced doses of nitrogen fertilizers (Hungría et al., 2020). In the process of infection of the root system of legumes, the virulence of nodule bacteria is important. If the specificity determines the spectrum of rhizobia, the virulence characterizes the activity of their action within a certain spectrum. The term virulence, denotes the ability of nodule bacteria to penetrate into the root tissue, multiply there and cause the formation of nodules. The virulence of the studied rhizobia was determined by the number of initiated nodules of different sizes and B. japonicum strain 634b showed high activity of forming the symbiosis with both soybean lines.

Fagorzi et al. (2021) showed that the response to root exudates involved hundreds of changes in the rhizobium transcriptome. Of the differentially expressed genes, 35% were influenced by the strain genotype, 16% were influenced by the plant genotype, and 29% were influenced by strain-by-host plant genotype interactions. Differences in nodulation rates between the photoperiodic insensitive (PPI) line with genotype e1e2e3 e4e5e7 and the short-day (SD) line with genotype E1e2e3(E4e5e7) were identified and it probably shows that E1 alleles interact with pathways which take part in control of forming nodules. Ferguson & Mathesius (2014) show that nodules are highly organized root organs that form in response to Nod factors produced by rhizobia, and they provide rhizobia with a specialized niche to optimize nutrient exchange and nitrogen fixation. Nodule development and invasion by rhizobia is locally controlled by feedback between rhizobia and the plant host. In addition, the total number of nodules on a root system is controlled by a systemic mechanism termed ‘autoregulation of nodulation’. Both the local and the systemic control of nodulation are regulated by phytohormones (Ferguson & Mathesius, 2014). But the results of our studies show that the inoculation of seeds under conditions of nitrogen deficiency significantly reduces the mass of the root system in the PPI line and SD-line plants compared to the control non-inoculated variant of the experiment. Co-inoculation slightly reduced the efficiency of the formation of the symbiotic apparatus, and stimulated the growth of the root system. This may indicate that soybean plants can control the number of nodules formed, based on the need for nitrogen and the amount of carbohydrates formed. In addition, starch content in leaves was significantly lower under conditions of inoculation, compared with the control. That may indicate a higher level of use of carbohydrates, since assimilative starch does not accumulate in the leaves.

In the current study we established that the nitrogen deficiency stimulated development of the root system of plants and the synthesized sugars were distributed predominantly to the root system growth (Table 1). Sucrose from the shoot is converted to malate in the plant and imported across the symbiosome membrane and into bacteroids, where it fuels nitrogen fixation. The product of the nitrogen fixation is then exported back to the plant, where it is assimilated into ureides for export to the shoot (Udvardi & Poole, 2013). We suppose that inoculation of seeds had extended sugar consumption to the symbiont due to which it compensates the lack of nitrogen, but leads to a slower growth of the root system. Rhizobial colonization of developing nodules takes just a few days and a visible root nodule begins to be seen (1 to 2 weeks after infection). Within the root nodule, the rhizobia enlarge and elongate to perhaps five times the normal size of rhizobia and change physiologically to forms known as bacteroids. Inoculation of seeds under conditions of nitrogen deficiency caused formation of large nodules located mainly on the main root, the low amount of microorganisms in the control caused formation of single small nodules which were situated only on the lateral roots (Fig. 3). Root nodules are lateral root organs, and like lateral roots they influence the architecture of the root system, then when they are exposed to fluctuations in the soil
these technologies for sustainable intensification of crop production. Determination of the amount of \( B. \) japonicum on MDA elective medium in the rhizosphere and rhizoplane showed that inoculation by \( B. \) japonicum strain 634b caused a significant increase in the amount of \( B. \) japonicum in the rhizosphere and rhizoplane in both soybean lines, in comparison with non-inoculated seeds (Fig. 5a, b). Then, co-inoculation by \( B. \) japonicum strain 634b + \( A. \) chroococcum significantly increased the amount of \( B. \) japonicum only in the rhizoplane and decreased their number in the rhizosphere. Scarcity of natural nitrogen fixers in the rhizosphere may constrain the diazotrophic contribution of fixed nitrogen to plants. Determination of the amount of \( A. \) chroococcum on the Ashby elective medium in the rhizosphere and rhizoplane showed that the inoculation by \( A. \) chroococcum strain 634b caused a significant decrease in the amount of \( A. \) chroococcum both in the rhizosphere and in the rhizoplane of the PPI line of soybean, and in the rhizosphere of the SD line, in comparison with non-inoculated seeds (Fig. 6a, b). However, the co-inoculation by \( B. \) japonicum strain 634b + \( A. \) chroococcum in the SD line significantly increased the number of \( A. \) chroococcum in the rhizoplane and decreased their number in the rhizosphere, in the PPI line their number decreased in the rhizoplane and increased in the rhizosphere, in comparison with non-inoculated seeds. We observed that the inoculant \( B. \) japonicum strain 634b suppresses the growth of \( A. \) chroococcum both in the rhizosphere and in the rhizoplane (Fig. 6a, b). That can testify to the competitive interaction of these microorganisms.

Conclusion

In conclusion, it was established that the nitrogen deficiency stimulated development of the root system of plants and the synthesized sugars were distributed predominantly to the root system growth. Probably, the E genes (their dominant and/or recessive state) of soybean isolines affect the regulation of the content and distribution of carbohydrates. We suppose that inoculation of seeds had extended sugar consumption to the symbiont, due to which it causes the lack of nitrogen, but leads to a slower growth of the roots. Nitrogen deficiency reduced the number of days from sowing to flowering in both soybean lines by 3–5 days compared to plants grown from bacterized seed. The obtained results proved the potential of the \( B. \) japonicum strain 634b inoculant for soybean in terms of increased symbiotic performance, especially under nitrogen deficiency conditions. This study indicated that inoculants could provide faster formation of the symbiotic system – Bradyrhizobium complex. Differences in nodulation rates between photoperiodic insensitive line with genotype el/e2c3 (ElecSE7) and short-day line with genotype El/e2c3/ElecSE7, were identified and it probably shows that El alleles interact with the pathway which take part in control of forming nodules. As a result of the performed studies, we determined antagonistic activity of \( B. \) japonicum strain 634b towards local population of diazotrophs of the genus Azotobacter spp. Furthermore, determination of the amount of \( B. \) japonicum on the medium of mannitol-yeast agar in the rhizosphere and rhizoplane showed that inoculation by \( B. \) japonicum strain 634b caused a significant increase in the amount of \( B. \) japonicum in the rhizosphere and rhizoplane in both soybean lines, in comparison with non-inoculated seeds. In addition, the studies carried out under controlled conditions will need to be extended into the field to test yield. The search for systemic interactions between host genes and strains of effective nitrogen fixers will lead to efficient production of crops and accelerate the development and application of these technologies for sustainable intensification of crop production.

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