

Title: Phosphate Deficiency Negatively Affects Early Steps of the Symbiosis between Common Bean and Rhizobia

Mariel C. Isidra-Arellano^{1,2#}, María del Rocío Reyero-Saavedra^{1#}, Maria del Socorro Sánchez-Correa¹, Lise Pingault³, Sidharth Sen^{4,5}, Trupti Joshi^{4,5,6}, Lourdes Girard⁷, Norma A. Castro-Guerrero⁸, David G. Mendoza-Cozatl⁸, Marc Libault³, Oswaldo Valdés-López^{1*}

¹ Laboratorio de Genómica Funcional de Leguminosas. Facultad de Estudios Superiores Iztacala, Universidad Nacional Autónoma de México. Tlalnepantla, Estado de México, 54090, México.

² Posgrado en Ciencias Biológicas, Universidad Nacional Autónoma de México. Coyoacan, Ciudad de México, 04510, México.

³ Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Beadle Center, Lincoln, 68503, USA.

⁴ Informatics Institute, C. S. Bond Life Sciences Center, University of Missouri, Columbia, MO, 65211, USA.

⁵ Christopher S. Bond Life Sciences Center, University of Missouri, Columbia, MO, 65211, USA.

⁶ Department of Health Management and Informatics, School of Medicine, University of Missouri, Columbia, MO. 65211, USA.

⁷ Departamento de Biología de Sistemas y Biología Sintética, Centro de Ciencias Genómicas, Universidad Nacional Autónoma de México. Cuernavaca, Morelos, 62210, México

⁸ Plant Sciences, Christopher S. Bond Life Sciences Center, University of Missouri, Columbia, MO, 65211, USA.

These authors have contributed equally to this work

***Correspondence:** E-mail: oswaldovaldesl@unam.mx. Phone: (+52) 555-623-1333 Ext: 39836.

ABSTRACT

Phosphate (Pi) deficiency reduces nodule formation and development in different legume species including common bean. Despite the significant progress in the understanding of the genetic responses underlying the adaptation of nodules to Pi deficiency, it is still unclear whether this nutritional deficiency interferes with the molecular dialog between legumes and rhizobia, if so, what part of the molecular dialog is impaired? In this study, we provide evidence demonstrating that Pi deficiency negatively affects critical early molecular and physiological responses required for a successful symbiosis between common bean and rhizobia. We demonstrated that the infection thread formation and the expression of *PvNSP2*, *PvNIN*, and *PvFLOT2*, genes controlling the nodulation process, were significantly reduced in Pi-deficient common bean seedlings. Further transcriptional analysis revealed that the expression of hormones-related genes is compromised in Pi-deficient seedlings inoculated with rhizobia. Additionally, we showed that regardless of the presence or absence of rhizobia, the expression of *PvRIC1* and *PvRIC2*, two genes participating in the autoregulation of nodule number, was higher in Pi-deficient seedlings than in control seedlings. The data presented in this study shed light on the understanding of how Pi deficiency impacts the early steps of the symbiosis between common bean and rhizobia.

Keywords: Phosphorus deficiency, common bean, rhizobia, molecular dialog, symbiosis, gene transcription.

1. Introduction

Phaseolus vulgaris (common bean) represents the principal source of non-animal proteins and minerals for human consumption in the developing world [1]. Additionally, common bean also provides a variety of secondary metabolites with analgesic and neuroprotective properties [2-3]. Like other legumes, common bean is able to symbiotically interact with nitrogen-fixing soil bacteria (rhizobia) and incorporates the fixed-nitrogen (e.g., ammonium) into the food chain [1]. Because of these agronomical, medical and ecological properties, common bean is one of the most important legumes worldwide.

To establish a symbiosis with rhizobia, a molecular dialog between legumes and these soil microbes is required. This molecular dialog begins with the detection of legume-derived flavonoids by compatible rhizobia [4-5]. In response, rhizobia produce diffusible nodulation factors (NF), which are perceived by legumes via the LysM-domain receptor kinase Nod Factors Receptor5 (NFR5) and NFR1, both located at the root hair plasma membrane, and likely by the epidermal LysM receptor eNFR [6-7]. Upon NF perception, a wide variety of molecular responses occur, which are crucial to activate the cellular responses required for rhizobial infection and the formation of the new organ termed nodule [8]. For instance, some of these molecular responses are required to modify the polar growth of the root hair leading to the formation of a curled tip [9-10]. In the center of this curl, an infection chamber is formed, where rhizobia are entrapped and multiply to form a micro-colony [11]. Immediately, an infection thread is initiated from the infection chamber and elongates through the root cortex where is located the nodule primordium [11-12]. Rhizobia are loaded into the infection thread and subsequently released into the nodule primordium cells, where, they are differentiated into bacteroids. Then, through the activity of the nitrogenase, the bacteroids fix and assimilate the atmospheric dinitrogen within the plant nodule [13].

Root infection and colonization by rhizobia and nodule formation are controlled by two independent genetic programs, which are tightly coordinated by a core of symbiosis-related genes that conform the so-called “common symbiosis pathway” [8,14]. Among these core genes, the leucine-rich repeat (LRR) receptor-like kinase SYMRK along with the plasma-membrane receptor NFR5 and NFR1 are required to detect and decode the NF signal [15-16]. Downstream to NF perception, different ion channels (e.g., the potassium channel Castor/Pollux and the calcium channels belonging to the CNGC15s family) and nucleoporins (e.g., NENA, NUP83 and NUP85) are activated to initiate and maintain rapid oscillations of the nuclear and perinuclear calcium concentrations (i.e., calcium spiking) [17-21]. These fluxes of calcium are further transduced by a calcium and calmodulin-dependent protein kinase (CCaMK), which, in turn, phosphorylates

the transcription factor CYCLOPS [22-23]. CYCLOPS is required to activate other critical transcription factors, including Nodulation Signaling Pathway2 (NSP2), Nodule Inception (NIN), Nuclear-Factor YA (NF-YA) and NF-YB as well as Ethylene Responsive Element1 (ERN1) [23-25]. The coordinated action of these transcription factors is essential to activate the expression of the genes required for the infection of root hairs by rhizobia [8, 14]. Among them, *Flotillin2* (*FLOT2*), which is crucial for the formation of the infection thread [26]. In parallel, a second genetic program triggering the formation of the nodule meristem in the roots is activated [8, 13]. It has been demonstrated that a delicate balance between the phytohormones auxins, cytokinins, and ethylene is required to trigger formation of the nodule meristem [10, 27-28]. Genetic analyses have revealed that mutations in the receptors or transporters of these phytohormones seriously affect nodule development. For instances, mutations in the cytokinins receptor MtCRE1/LjLHK1 or in the central regulator of the ethylene signaling EIN2 lead to spontaneous nodulation or over-formation of nodules in the legume models *Lotus japonicus* and *Medicago truncatula*, respectively [29-30].

Because symbiotic nitrogen fixation (SNF) is a high-energy demanding process, legumes tightly regulate the number of infections and nodules per plant [31]. This autoregulation of nodulation (AON) process is locally- and systemically activated by the legume. At the systemic level, the plant-derived CLAVATA3/embryo-surrounding region (CLE) peptides are considered as critical regulators of the AON process [31]. In common bean two AON CLE peptide-encoding genes have been identified, *Rhizobia-Induced CLE1* (*PvRIC1*) and *Rhizobia-Induced CLE2* (*PvRIC2*) [32]. *PvRIC1* expression is induced as early as one-day post rhizobia inoculation, whereas *PvRIC2* expression is approximately induced five days upon rhizobia inoculation [32]. *PvRIC1* and *PvRIC2* peptides are synthesized in the root and translocated to the leaves via xylem. Upon perception of *PvRIC1* and *PvRIC2* peptides by a Leucine-rich Repeat Receptor-like Kinase (LRR-RLK) called *PvNARK*, the expression of different genes participating in the negative regulation of the meristematic activity of the nodule primordium cell is activated [31-32]. It has been widely demonstrated that mutations in the *PvNARK/GmNARK/LjHAR1/MtSUNN* receptor lead to a hypernodulation phenotype along with a reduction in the plant growth [32-36].

Most of the arable soils where common bean is produced have low levels of phosphorus (P), an essential macronutrient required for optimal plant growth and development. Common bean, like other plants, exclusively uptakes P from the soil as inorganic phosphorus (i.e., orthophosphate, Pi) [37-38]. However, soil Pi rapidly interacts with Fe³⁺, Ca²⁺, and Al³⁺ ions, forming complexes making Pi unavailable for plant uptake [39]. Pi deficiency constrains common bean growth and productivity, and even affects its ability to form nodules and symbiotically fix

nitrogen [40]. It has been reported that Pi deficiency decreases common bean nitrogen-fixation efficiency by increasing the permeability of the nodule to oxygen leading to the inactivation of the rhizobia-biosynthesized nitrogenase [41-42]. Furthermore, it has also been shown that Pi deficiency reduces by more than 60% the number of nodules in common bean plants (Hernández et al., 2009).

Different efforts to understand how legumes cope with Pi deficiency while symbiotically interacting with rhizobia have been made [43-46]. Physiological studies on different legumes have demonstrated that under Pi deficiency conditions, Pi is preferentially relocated from other organs to the nodules [47-52]. Furthermore, both transcriptional and metabolic studies in common bean, *Medicago truncatula*, and chickpea have revealed that most of the molecular responses of nodules are oriented to efficiently use internal Pi sources and maintain Pi homeostasis under limiting conditions [40, 43, 46]. For instances, it has been reported that the concentration of different organic acids (e.g., citrate, succinate and pyruvate), many of them participating in the cation exchange that is required for the Pi uptake, was differentially regulated in nodules of both common bean and chickpea plants [40, 43, 46]. Additionally, it has also been reported that the expression of flavonoid-synthesis related genes was diminished in Pi-deficient *M. truncatula* roots [43].

Although nodule efficiency and the molecular responses underlying the adaptation of this specialized organ to Pi deficiency has been studied, the molecular mechanisms leading to a reduction in nodule number under Pi deficiency remain unknown. For instance, it is still unclear whether Pi deficiency interferes with the molecular dialog between common bean and rhizobia, if so, what part of the molecular dialog is impaired?

In this study, we report the early molecular and physiological responses triggered by rhizobia in common bean seedlings growing under Pi deficiency conditions. A transcriptional analysis by quantitative real-time PCR (qRT-PCR) revealed that the expression of *PvNSP2*, *PvNIN* and *PvFLOT2*, was quickly reduced by 50% in Pi-deficient common bean seedlings. Although curled root hairs were observed regardless of the Pi condition (optimal or deficient condition), their number was severely reduced in Pi-deficient seedlings. Interestingly, the majority of the rhizobia-induced curled root hairs in Pi-deficient seedlings showed aberrant deformations that have previously been associated with defects in the rhizobia infection process. Additionally, we also observed that the expression of the *PvRIC1* and *PvRIC2* gene, regardless of the mock or rhizobia treatment, significantly increased in Pi-deficient seedlings. To get more insights about the transcriptional modifications leading to an inefficient communication between common bean and rhizobia under Pi-deficient conditions, we performed a genome-wide transcriptional analysis. This analysis revealed that the expression of genes

associated with early steps (e.g., signal transduction and hormone balance) of this symbiosis was affected in Pi-deficient plants. The data presented in this study pave the road to understand the genetic mechanisms underlying the establishment of the symbiosis between rhizobia and common bean under Pi-deficient conditions.

2. Material and Methods

2.1. Plant Material

Common bean (*P. vulgaris* L. cv Negro Jamapa) seeds were produced under greenhouse conditions in the Facultad de Estudios Superiores Iztacala, UNAM, at Tlalnepantla, Estado de Mexico, Mexico. Seeds were surfaced sterilized by soaking in 70% ethanol for 1 min, followed by treatment for 10 min with 10% bleach. Seeds were subsequently washed ten-times in sterile water. Sterilized seeds were germinated for three days at 25°C in Petri dishes containing wet and sterile germination paper (Anchor paper CO, St. Paul, MN, USA). Petri dishes containing common bean seeds were kept under dark conditions at 25 °C.

2.2. Bacterial Strains and culture conditions

Rhizobium tropici CIAT899 strain was used to inoculate common bean seedlings. *R. tropici* cells were grown for 2 days at 30°C on PY medium (5mg/l peptone; 3mg/l yeast extract) supplemented with 0.7M CaCl₂ and 20 µg/ml nalidixic acid. After two days, *R. tropici* cells were harvested and resuspended in sterile water at O.D₆₀₀ = 0.3. 1 ml of this bacterial suspension was used to individually inoculate common bean seedlings.

Escherichia coli DH5α strain carrying the plasmid pFAJ1700::pLacZ:GUS was used as a plasmid donor for triparental mating with *R. tropici*. *E. coli* cells were grown in Luria-Bertani (LB) broth supplemented with 10 µg/ml tetracyclin overnight at 37°C.

E. coli pRK2013 strain was used as a helper for triparental mating with *R. tropici*. pRK2013 cells were grown in LB broth supplemented with 30 µg/ml kanamycin overnight at 37°C.

R. tropici::GUS strain was obtained by triparental mating using the *E. coli* DH5α strain carrying the plasmid pFAJ1700::placZ:GUS, containing the *uidA* gene under the *lacZ* promoter as a donor, and the pRK2013 as conjugation helper. *R. tropici* derivatives carrying the plasmid were selected in PY medium as nalidixic acid (Nal) and tetracyclin (Tc) resistant transjugants. *R. tropici*::GUS cells were grown in PY medium supplemented with 0.7M CaCl₂, 10 µg/ml Tc, and 20 µg/ml Nal for 2 days at 30°C. After two days, cells were harvested and resuspended in sterile water at OD_{600nm} = 0.3. 1 ml of this bacterial suspension was used to individually inoculate common bean seedlings.

2.3. Treatment

Three-days old common bean seedlings were transferred into a nitrogen-free Fähræus medium [53] plates supplemented with 1mM PO₄ (optimal-Pi conditions) or 5 µM PO₄ (Low-Pi conditions). Three days after transplanting, seedlings were inoculated with autoclaved-water (Mock) or with *R. tropici* CIAT899. Inoculated seedlings were kept under dark conditions at room temperature. At 1, 24 and 48 hours post-inoculation, the zone of the roots

susceptible to rhizobium infection (hereafter referred as susceptible zone) was isolated, flash frozen in liquid nitrogen, and stored at -80°C until used for total RNA extraction. The susceptible zone encompassed a region of ~ 1cm and is analogous to the distal region of the elongation zone and the entire differentiated zone of the root [54]. Four biological replicates, each one containing susceptible zones from four different seedlings, were independently generated.

2.4. Quantification of Soluble Pi

Soluble Pi content was determined in roots from common bean seedlings grown for three days in optimal- or low-Pi conditions using the colorimetric assay reported in [55]. Briefly, roots were harvested, rinsed with ultra-pure water, weighed, immediately homogenized in 10N trichloroacetic acid and fractioned by centrifugation. Soluble fraction was incubated with the staining solution (350mM FeSO₄, 16% (NH₄)₆Mo₇O₂₄) for 10 minutes at room temperature. Optical density was determined at 660nm. For each experimental condition, five replicates, each one containing four roots from different seedlings, were analyzed.

2.5. Root hair deformation analysis

Three-days old common bean seedlings grown for three days under optimal-Pi or low-Pi conditions were inoculated with 1 ml of *R. tropici* suspension (OD_{600nm}= 0.3). Forty-eight hours after inoculation, roots were collected and stained with methylene blue to maximize contrast, and then observed with a bright-field microscope. A total of 20 independent biological replicates were generated, each one including 10 plants.

2.6. Quantification of number of infection thread

To quantify the number of infection thread per root, common bean seedlings grown for three days under optimal-Pi or low-Pi conditions were inoculated with 1 ml of *R. tropici*::GUS suspension (OD_{600nm}= 0.3). Three days post-inoculation, roots were collected, rinsed twice with autoclaved ultra-pure water and immersed in GUS staining solution (0.05% 5-bromo-4-chloro-3-indolxyl-β-D-glucuronic acid, 100 mM sodium phosphate buffer (pH7), 0.5 mM potassium ferrocyanide, 0.5 mM potassium ferricyanide, 10 mM Na₂EDTA and 0.1% Triton X-100) and incubated for one hour at 37°C. After rinsing in phosphate buffer, the number of infection thread formed at the susceptible zone was quantified under a bright-field microscopy. For this experiment, four biological replicates, each one with ten roots from different seedlings, were included.

2.7. Gene expression analysis

To analyze the expression of *PvNSP2*, *PvNIN*, *PvFLOT2*, *PvRIC1* and *PvRIC2* genes, total RNAs were extracted from 0.5g of rhizobia-inoculated or mock-inoculated roots from common bean seedlings growing under optimal-Pi or low-Pi conditions using ZR Plant RNA Miniprep kit (Zymo Research, Irvine, CA, USA) according to manufacturer's instructions. Genomic DNA (gDNA) was removed

from purified RNA using DNaseI RNase-free (Thermo Fisher Scientific, USA) according to the manufacturer's instructions. 1 µg of gDNA-free total RNA was used to synthesize cDNA using Thermo Scientific RevertAid Reverse Transcriptase (Thermo Fisher Scientific, USA) according to manufacturer's instructions. cDNA samples were used to analyze the expression of the above-mentioned genes by quantitative real-time PCR (qRT-PCR) in a Step-One qPCR thermocycler (Applied Biosystems, USA). The housekeeping gene *PvActin* was used to normalize gene expression levels [56]. The expression level of different genes was calculated according to the equation $E = P_{\text{eff}}^{-\Delta C_t}$ where P_{eff} is the primer set efficiency calculated using LinRegPCR [57] and ΔC_t is the difference of the cycle threshold (C_t) values of the housekeeping gene and a given gene. qRT-PCR primers were designed by using the online available software Primer 3 v.0.4.0 [58] and using the following parameters: 80-120pb as product size, 19-23nt as primer size, 60°C as primer temperature melting, and 40-60% of primer GC content. To design primers, the sequence from the 3'UTR region of each gene was obtained from the *P. vulgaris* genome Version 2.1 [59-60]. The nucleotide sequences of the qRT-PCR primers used in this study are provided in Table S1. For this experiment, four biological replicates, each one containing roots from four different seedlings, were included.

2.8. Preparation of messenger RNA-seq library and High-throughput sequencing

Total RNA was isolated from 0.5g of 48-hours rhizobia-inoculated or mock-inoculated roots from common bean plants growing under optimal-Pi or low-Pi conditions, as described earlier in this paper. Stranded messenger RNA-seq (mRNA-seq) libraries were generated from 1.5 µg of gDNA-free total RNA from each experimental condition and prepared using TruSeq RNA Sample Prep kit (Illumina, San Diego, CA, USA) according to the manufacturer's instructions. Briefly, sample concentration was determined by Qubit fluorometer (Invitrogen, Carlsbad, CA, USA) using the Qubit HS RNA assay kit, and the RNA integrity was checked using the Fragment Analyzer automated electrophoresis system (Advanced Analytical, Ankeny, IA, USA). Poly-A containing mRNAs were purified from total RNAs and subsequently fragmented. cDNAs were generated from fragmented RNAs, and the index-containing adapters were ligated to their ends. The amplified cDNAs were purified by addition of Axyprep Mag PCR Clean-up beads (Axygen, Corning, NY, USA). The quality of each purified RNA-seq library was evaluated using the Fragment Analyzer automated electrophoresis system, and quantified with the Qubit fluorometer using the Qubit HS dsDNA assay kit.

In total, twelve-stranded mRNA-seq [two Pi conditions (sufficient and deficient), two treatments (mock or rhizobia), and three independent biological replicates] were high-throughput sequenced in 75 bp single-end at the University of Missouri DNA Core Facility by using an Illumina NextSeq500 sequencer

(Illumina, USA) according to the manufacturer's instructions. Image analysis and base calling were performed using the Illumina pipeline (<http://www.illumina.com>).

2.9. Mapping and processing mRNA-seq reads

mRNA-seq analysis was conducted using a custom in-house developed informatics pipeline which first performs a quality check on the raw sequencing fastq files using the tool fastqc [61] and trim-galore tool [62] to remove low quality reads and trim adaptor sequences. We then indexed the *P. vulgaris* Version 2.1 [59-60] reference genome using Bowtie2 short read aligner [63]. The trimmed mRNAseq reads were then aligned, allowing two mismatches, to this index reference genome using TopHat, which also reports splice junction sites [64].

2.10. Quantification and Identification of Differentially regulated genes

The next step in our pipeline was to quantify the expression level of each transcript/gene by measuring the level of mRNA-seq alignments using the tool Cufflinks [65]. The quantified expression level was represented by Fragments per Kilobase of transcript per Million mapped reads (FPKM) values. The differential expression levels of quantified genes were then calculated using the tool Cuffdiff [65] which takes the observed log fold change of a gene's expression from control & treatment samples and then reports if the gene is significantly differentially expressed (q -values). The thresholds for Cuffdiff were set at 2-fold change and q -value ≤ 0.05 before calling genes to be differentially expressed, which are usually annotated with their unique identifiers defined by the gene models annotation and gene coordinates files.

2.11. Gene functional classification

The biological relevance of the differentially regulated genes was assessed by a gene function enrichment analysis using the method Singular Enrichment Analysis (SEA) available in the web-based tool AgriGo [66-67], followed by a summarization and visualization of statistically significant non-redundant Gene Ontology (GO) terms by using the web-based tool REVIGO [68-69]. Briefly, GO terms enriched in each set of genes were compared to the *P. vulgaris* Version 2.1 gene reference background [59-60]. P -values for the GO terms were obtained through Fisher's exact test, and a q -value was computed to produce lists of significant GO terms with an estimated FDR of 5%. Enriched GO terms with $q < 0.05$ were further summarized and visualized on REVIGO. Additionally, MapMan gene functional classification was used [70-71]. For MapMan analysis, the common bean mapping file, available at MapMan website [72], was used.

2.12. Statistical analyses

All the statistical analyses were conducted using R software 3.0.1. The specific tests performed are indicated in the legend of the corresponding figure.

3. Results and Discussion

3.1. Rhizobia-induced root hair deformation and infection thread formation is affected in Pi-deficient common bean seedlings

It has been demonstrated that the reduction in nodule number is one of the negative effects of Pi deficiency in legumes [40]. However, it is unclear whether this nutritional stress interferes with the molecular dialog between common bean and rhizobia, and therefore, the stages of this molecular dialog that might be affected by Pi deficiency remain unknown. To get insight in the effect of the Pi deficiency in the molecular dialog between common bean and rhizobia, we first developed a system allowing us to track early molecular and physiological responses to rhizobia under limiting Pi conditions. This system consisted in growing common bean seedlings on optimal- (1mM) or low- (5 μ M) Pi conditions under sterile and controlled environmental conditions (Figure S1). By using this system, we were able to obtain Pi-deficient common bean seedlings, which was reflected by a 50% reduction in plant Pi contents (Figure S1). Once we confirmed that our experimental system yields Pi-deficient common bean seedlings, we proceeded to assess early responses to rhizobia in common bean seedlings growing under optimal-Pi or low-Pi conditions.

One of the early physiological responses triggered by rhizobia is the root hair deformation, which is required for rhizobia entrapping and the formation of the infection chamber [9-10]. To test whether Pi deficiency affects the rhizobia-induced root hair deformation and infection thread formation, common bean seedling growing for three days under optimal-Pi or low-Pi conditions were inoculated with *R. tropici* CIAT899::GUS. Forty-eight hours post inoculation, 95% (n=190) of the seedlings growing under optimal-Pi conditions showed characteristic rhizobia-induced root hair deformation (Fig 1a and 1c), whereas only 50% (n=200) of the Pi-deficient seedlings did (Fig 1b and 1c). Interestingly, most of the deformations observed in Pi-deficient common bean seedlings were aberrant (Fig 1d). For instance, we observed root hairs with swelled tip, with more than one outgrowth from a single root hair tip, and spatula-like deformation (Fig 1e). Additionally, we observed that Pi deficiency significantly affected rhizobia attachment, which was reflected by a faint blue staining (as a product of the activity of the *R. tropici*::GUS strain) at the susceptible zone (Fig 2a). Accordingly, we observed that Pi-deficient common bean seedlings developed 60% less infection thread than seedlings growing under optimal-phosphate condition and inoculated with rhizobia (Fig 2b-d). Similar aberrant rhizobia-induced root hair deformations have been observed in *M. truncatula* *ern1/ern2*, *M. truncatula* *dmi1* and in *L. japonicus* *scarn* mutant plants [9, 53, 73-74]. This defect has been associated to inhibition in the polar growth of the root hair cells, which affects the rhizobia infection process, including the infection thread formation [9, 73-74]. Additionally,

an early study reports that Pi deficiency affects the rhizobia attachment to *Medicago* roots, as we observed in this study [75]. Thus, our data suggest that Pi deficiency negatively affects the polar elongation of the root hairs likely leading to inefficient attachment and entrapping of rhizobia.

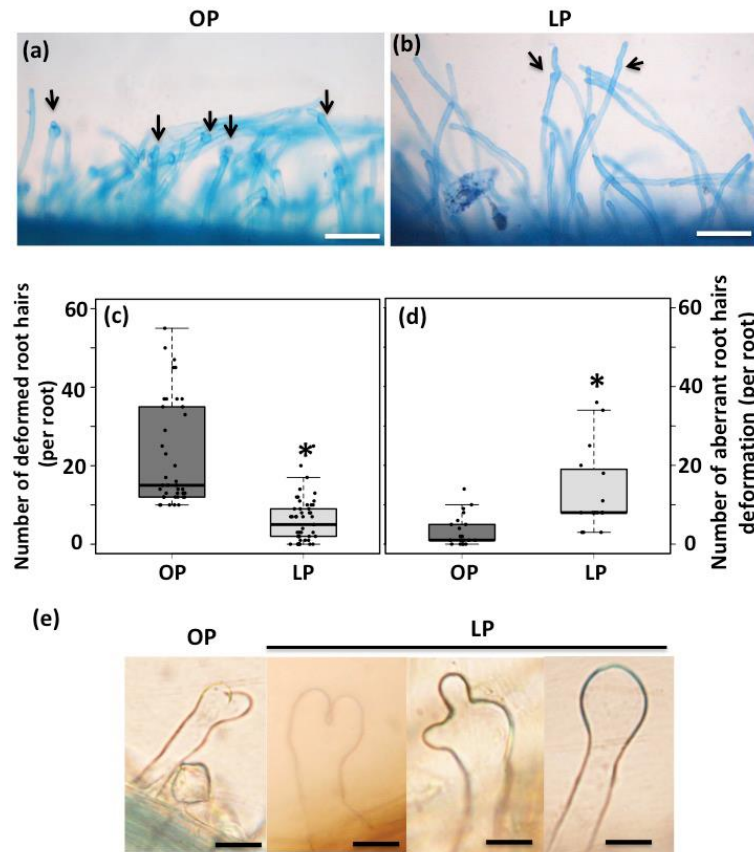


Figure 1: Pi deficiency negatively affects the rhizobia-induced root hairs deformation in common bean

Rhizobia-induced root hairs in common bean seedling growing under optimal-Pi (OP) (a) or low-Pi (LP) conditions (b). Scale bars in panel represent 100 μ m. Arrows indicate some examples of the rhizobia-induced root hairs observed in both OP or LP-conditions (c) Number of rhizobia-induced root hair deformation in common bean seedlings growing under OP- conditions or LP-conditions. (d) Number of non-effective rhizobia-induced root hair deformation in common bean seedlings growing under OP-conditions or LP-conditions. Asterisk indicates a significant difference according to One-way ANOVA (p -value<0.001). Data showed was obtained from 20 biological replicates, each one containing ten roots from different common bean seedlings. (e) Types of aberrant rhizobia-induced root hair deformation observed in common bean seedlings growing under LP-conditions. Scale bars in panel represent 50 μ m.

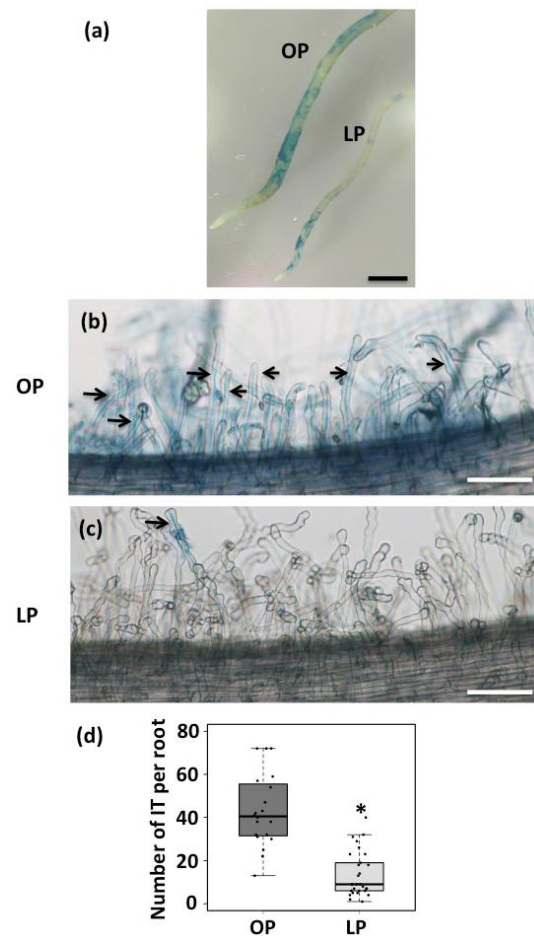


Figure 2: Pi deficiency reduces rhizobia attachment and infection thread formation in common bean

(a) Rhizobia attachment in roots from common bean seedlings growing under optimal-Pi (OP) or low-Pi conditions (LP). Seedlings were inoculated with *R. tropici*::GUS and stained by the β -glucorinidase activity. Scale bars in panel represent 2mm. Infection thread formation in common bean seedlings growing under OP (b) or LP-conditions (c). Arrows indicates some examples of the infection thread observed in OP or LP conditions. Scale bars in panel represent 100 μ m. (d) Number of infection thread (IT) per root. Asterisk indicates a significant difference according to One-way ANOVA (p-value<0.001). Data showed was obtained from 20 biological replicates, each one containing ten roots from different common bean seedlings.

3.2. Pi deficiency diminishes the expression of genes required for root hair curling and rhizobia infection

The coordinated action of different transcription factors is essential for a successful symbiosis with rhizobia. For instances, upon NF perception, the transcription factors NSP2 and NSP1 forms a DNA binding complex [76]. In turn,

the NSP2/NSP1 complex positively regulates the expression of the transcription factor *NIN*, which is required to activate the expression of different genes involving in rhizobia infection and colonization processes [77]. It has been demonstrated that mutations in the *NSP2* gene significantly affect the rhizobia-induced root hair deformation and rhizobia infection process, particularly in the formation of the infection chamber and infection thread [74, 78]. Likewise, early reports have demonstrated that *M. truncatula nin* mutants undergo excessive rhizobia-induced root hair curling but are impaired in infection and nodule formation [77].

The fact that Pi deficiency reduces both rhizobia-induced root hair deformation and infection thread formation in common bean seedlings, suggests that the expression of genes participating in the root hair curling and rhizobia infection is compromised under this nutritional condition. To test this hypothesis, we evaluated the expression of *PvNSP2* (Phvul.009G122700), *PvNIN* (Phvul009G115800), and *PvFLOT2* (Phvul.009G090700) in common bean seedlings growing under optimal-Pi and low-Pi conditions and inoculated with rhizobia. Our expression analysis revealed that the expression of these three symbiosis-related genes was induced upon one-, twenty-four and forty-eight hours post-inoculation with *R. tropici* in common bean seedlings growing under optimal Pi conditions (Fig. 3). In contrast, we observed a reduction by 50% in the fold-change of the expression of these three symbiotic genes in Pi-deficient common bean seedlings inoculated with rhizobia, (Fig 3). Interestingly, at forty-eight hours post-inoculation with rhizobia, *PvNIN* was the only gene that showed a substantial induction (in average by 5 fold-change) in Pi-deficient seedlings in response to rhizobia, whereas in optimal-Pi conditions the expression of this gene was repressed at this inoculation time-point (Fig 3b).

To provide an explanation about the reduction in the fold-change of these three symbiosis-related genes observed in Pi-deficient seedlings, we analyzed their expression levels in response to mock or rhizobia inoculation (Fig 4). By comparing the expression levels of *PvNSP2* and *PvNIN*, from both optimal-Pi and Pi-deficient seedlings, we did not find significant differences at one and twenty-four hours post-mock treatment (Fig 4a-b). Similarly, we did not find significant differences in the expression levels of *PvFLOT2* across the entire time-course analysis when comparing optimal-Pi and low-Pi seedlings post mock treatment (Fig 4c). At forty-eight hours, we observed an increase in the expression levels of *PvNSP2* and a diminution in the expression levels of *PvNIN* in mock-inoculated Pi-deficient seedlings, respectively. Finally, by comparing the expression levels obtained from mock- and rhizobia-inoculated Pi-deficient seedlings, we observed significant differences for *PvNSP2* and *PvNIN* only, which showed a significant increase in their expression levels upon twenty-four and forty-eight hours of inoculation with

rhizobia (Fig 4). Altogether, these expression data suggest that the defects in the root hair deformation and infection thread formation observed in common bean seedlings grown under Pi-deficient conditions, can be explained by an inefficient activation of critical transcription factors, like *PvNIN* and *PvNSP2*, as well as critical symbiotic genes like *PvFLOT2*. The fact that substantial induction of the expression of *PvNIN* in Pi-deficient seedlings was detected upon 48 hours post-inoculation with rhizobia only, also indicates that Pi deficiency delays the activation of critical symbiosis-related genes.

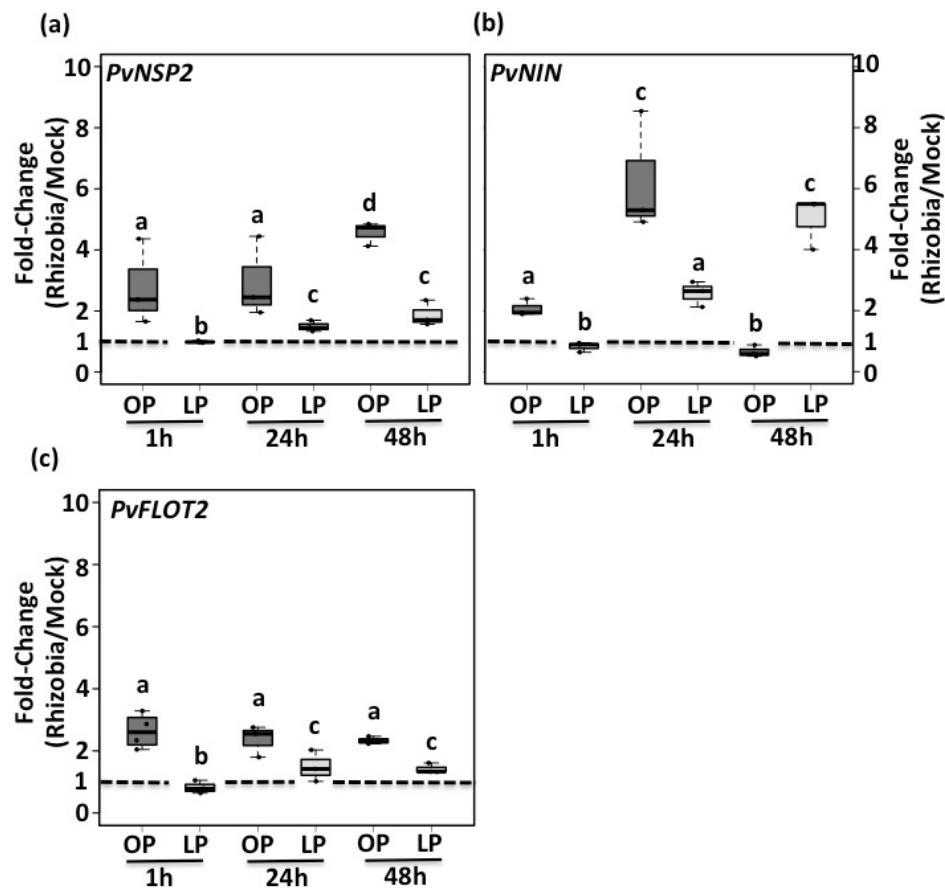


Figure 3: Pi deficiency reduces the activation of early symbiotic genes

Rhizobia-triggered expression of *PvNSP2* (a), *PvNIN* (b) and *PvFLOT2* (c) genes in common bean seedling growing under optimal-Pi (OP) or low-Pi conditions and inoculated with mock or rhizobia. Box plots represent first and third quartile (horizontal box side), minimum and maximum (outside whiskers). Data showed are the fold-changes (e.g., OPR/OPM) obtained from four independent replicates, each one containing susceptible zones from four different plants. One-way ANOVA, followed by a Tukey honest significant difference (HSD) test was performed (p-value < 0.01). Statistical classes sharing a letter are not significantly different. Dashed line shows basal expression (e.g., no induction triggered by rhizobia)

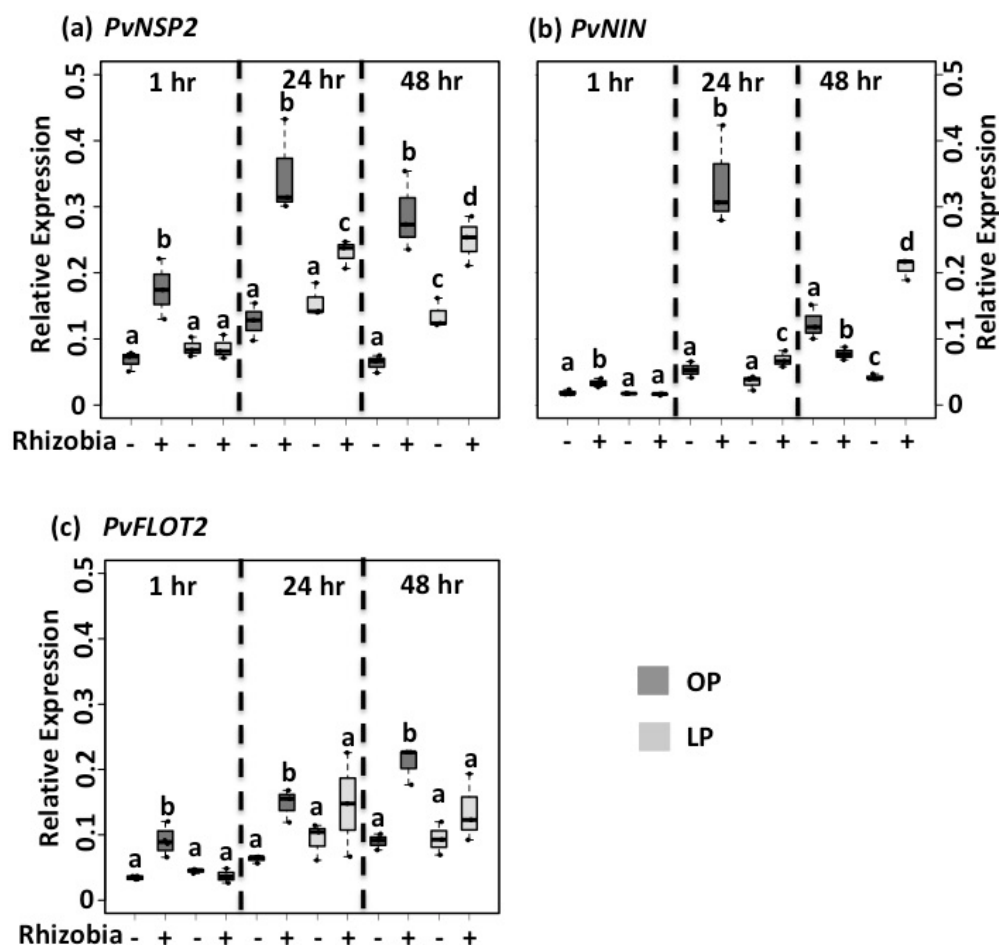


Figure 4: Expression levels of *PvNSP2*, *PvNIN*, and *PvFLOT2* in response to rhizobia in common bean seedlings

Expression levels of *PvNSP2* (a), *PvNIN* (b) and *PvFLOT2* (c) genes in common bean seedlings grown under optimal-Pi (dark-gray) or low-Pi (light-gray) conditions and inoculated with mock (-) or rhizobia (+). Box plots represent first and third quartile (horizontal box side), minimum and maximum (outside whiskers). Data showed was obtained from four independent replicates, each one containing susceptible zones from four different plants. One-way ANOVA for each time point, followed by a Tukey honest significant difference (HSD) test was performed (p -value < 0.01). Statistical classes sharing a letter are not significantly different.

3.3. Pi deficiency increase the expression of the *PvRIC1* and *PvRIC2* genes in common bean seedlings

It has been reported that the expression of the *PvRIC1* and *PvRIC2* is induced one- and five-days post-inoculation with rhizobia, respectively [32]. Based

on the fact that Pi deficiency triggers a reduction in the number of nodules in common bean [40] and that the peptides PvRIC1 and PvRIC2 actively participate in the AON process, we hypothesized that the expression of *PvRIC1* and *PvRIC2* might be affected in Pi-deficient common bean seedlings. To test this hypothesis, we assessed the expression of *PvRIC1* (Phvul.005G096901) and *PvRIC2* (Phvul011G135900) in common bean seedlings grown under optimal- or low-Pi conditions and inoculated with mock or rhizobia. This analysis revealed that the expression of *PvRIC1* is induced as early as one-hour post inoculation with rhizobia in both control and Pi-deficient common bean seedlings and have its maximum induction level at forty-eight hours post-inoculation with rhizobia (Fig 5 a-b). In contrast, we were not able to detect a consistent and reproducible induction of *PvRIC2* at one and twenty-four hours post-inoculation with rhizobia. We detected a clear induction of *PvRIC2* in response to rhizobia in both control and Pi-deficient common bean seedlings after forty-eight hours post-inoculation (Fig 5c). Although the induction of these two AON-related genes was observed in both control and Pi-deficient seedlings, we observed that the expression levels of both *PvRIC1* and *PvRIC2* genes were always higher in Pi-deficient seedlings than in control seedlings. Additionally, by comparing the expression levels of mock-inoculated seedlings, we observed that Pi-deficient seedlings always showed higher expression levels similar to those observed in control-seedlings inoculated with rhizobia (Fig 5a-c). Altogether, these data indicate that Pi deficiency induces the expression of *PvRIC1* and *PvRIC2* in the absence of rhizobia, and that the expression of these AON-related genes is highly induced in response to rhizobia in Pi-deficient common bean seedlings. Under this scenario, it is likely that: 1) Pi-deficient common bean seedlings are preconditioned to reduce the number of rhizobia infections. This hypothesis can be supported by the fact that the overexpression of RIC1 and RIC2 inhibits nodulation in soybean [79]. 2) Based on the fact that other CLE peptides (e.g., CLE14) [80] play a critical role in the plant adaptation to Pi deficiency [81-82], it is tempting to speculate that higher expression of *PvRIC1* and *PvRIC2* in response to Pi deficiency might be critical for common bean to properly adapt to Pi deprivation.

3.4. mRNA-seq analysis

To obtain better insight into the genetic responses of common bean plants leading to a reduced nodulation under Pi-deficient conditions, we conducted an mRNA-seq analysis. For this genome-wide transcriptional analysis, based on our transcriptional data obtained by qRT-PCR, we selected forty-eight hours post-inoculation to capture more transcriptional responses to rhizobia.

A total of 12 cDNA libraries were generated from control (optimal Pi: OP) and Pi-deficient roots (low Pi: LP) inoculated forty-eight hours with mock (OPM or LPM, respectively) or rhizobia (OPR or LPR, respectively). Three independent

biological replicates were generated for each condition. These libraries were sequenced using the Illumina NextSeq500 platform. After filtering low quality reads, a total of 176,365,724 single-end reads (75bp) were aligned to the *P. vulgaris* genome reference sequence Version 2.1 [59-60] using Bowtie and Tophat software and allowing two mismatches [64]. Of these, 164,037,947 were uniquely mapped to the common bean genome and were used for further analysis. The full RNA-seq datasets generated from the 12 cDNA libraries used in this study were deposited in the Gene Expression Omnibus [83] under the accession number GSE118968.

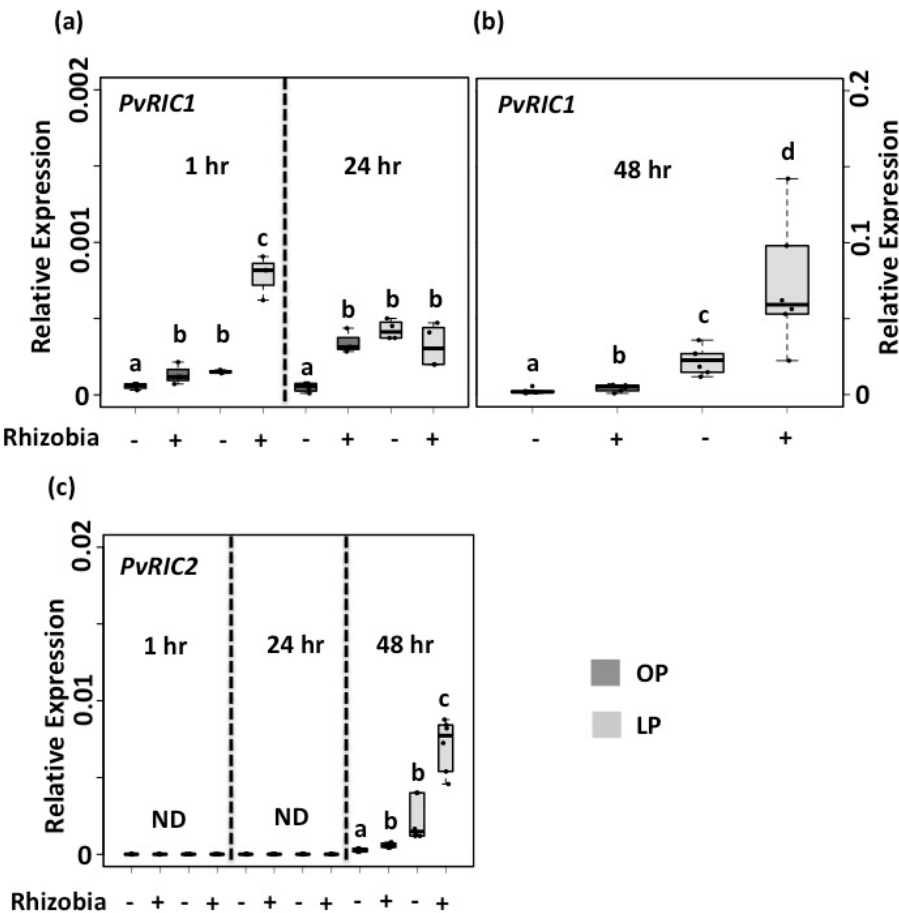


Figure 5: Pi deficiency increases the expression of *PvRIC1* and *PvRIC2* even in the absence of rhizobia

Expression levels of *PvRIC1* at one-, twenty-four- (a) and forty-eight hours (b) post inoculation with mock (-) or rhizobia (+) in common bean seedlings growing under optimal-Pi (OP) or low-Pi (LP) conditions. (c) Despite several attempts, we were not able to detect reproducible and consistent expression (non-detected: ND) of *PvRIC2* at one and twenty-four hours post-inoculation with mock or rhizobia. Data showed was obtained from four independent replicates, each one containing susceptible zones from four different plants. One-way ANOVA, followed by a Tukey honest significant difference

(HSD) test was performed (p -value < 0.01). Statistical classes sharing a letter are not significantly different.

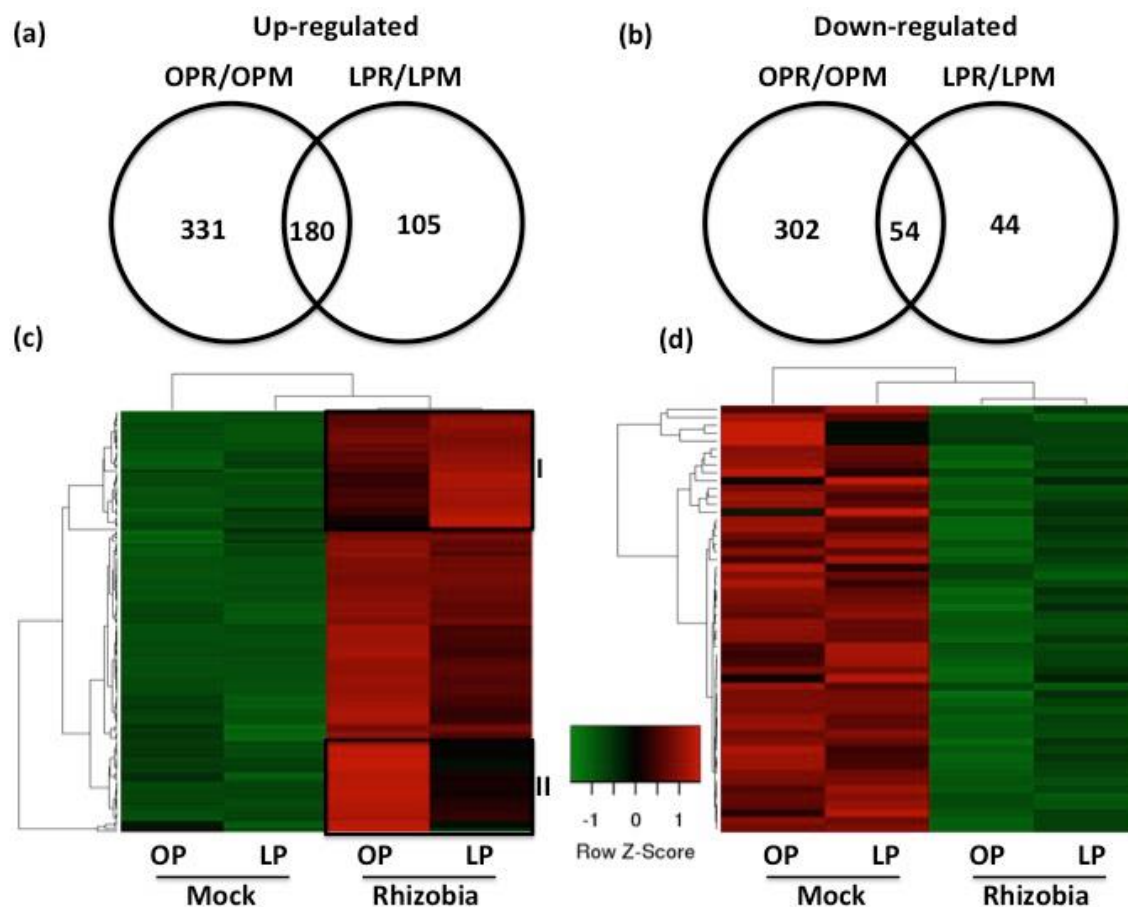


Figure 6: Expression of rhizobia-responsive genes is affected in Pi-deficient common bean seedlings

Number of over-lapping and non-overlapping up-regulated (a) or down-regulated (b) rhizobia-induced genes among common bean seedlings grown under optimal-Pi (OP) or low-Pi (LP) conditions and inoculated with rhizobia (R) during 48 hours. Differentially regulated genes in each Pi conditions were identified by Cuffdiff at FDR<0.05, with an additional cutoff of two-fold in a pairwise comparison between treatments (eg., OPrhizobia/OPmock). Over- and non-overlapping genes were identified after a pairwise comparison between the differentially regulated genes identified in each Pi conditions. Heat map showing the expression levels of up-regulated genes (c) or down-regulated genes (d) from common bean seedlings growing under OP or LP conditions and inoculated with mock or rhizobia. Expression levels were false colored. Genes showing higher expression levels are shown in different scales of red color, whereas genes showing lower expression levels are showed in different scales of green color.

3.5. Global transcriptional responses of Pi-deficient common bean seedlings interacting with rhizobia

In order to identify additional genes with a potential role in the regulation of the early stages of the symbiosis between common bean and rhizobia under low-Pi conditions, the mRNA-seq data sets were analyzed using Cuffdiff [84] with an additional cutoff of 2-fold in pairwise comparisons (e.g., OPR/OPM). In total, 867 (511 up-regulated and 356 down-regulated) and 383 (285 up-regulated and 98 down-regulated) differentially regulated genes were identified when comparing OPR/OPM and LPR/LPM, respectively (Tables S2-S3). Among them, *PvNSP2* (Phvul.009G122700) and *PvFLOT2* (Phvul.009G090700) were also classified as differentially regulated by mRNA-seq approach (Table S2-S3). However, we did not detect the expression of *PvNIN* (Phvul009G115800) in our mRNA-seq analysis, which we explain by a difference in the sensitivity of mRNA-seq and qRT-PCR approaches.

To confirm these mRNA-seq results, the expression of 25 randomly selected genes was analyzed via qRT-PCR and using independent biological material from the one used for mRNA-seq analysis (Fig. S2). The expression pattern obtained by qRT-PCR showed the same trend observed by mRNA-seq in response to rhizobia. We found some differences in the fold-change computed by the two independent methods, which we explain by the relative sensitivity and data processing (e.g., algorithms used for data normalization) of each method, along with technical and biological aspects (e.g., efficiency/specificity of qRT-PCR and inherent variation in the responses of common bean to both Pi availability and rhizobia). In spite of these differences, the fold-changes computed for each analyzed gene by qRT-PCR were statistically different between both Pi conditions.

Upon confirmation of the reliability of our mRNA-seq datasets, we performed additional pairwise comparisons to identify genes that might explain the reduction in the nodule number triggered by Pi deficiency. To this end, we compare the differentially regulated genes found in the pairwise comparisons OPR/OPM and LPR/LPM to identify commonly and uniquely regulated genes under these Pi conditions and interacting with rhizobia. This comparative analysis revealed that 234 (180 up-regulated and 54 down-regulated) genes were commonly regulated in both Pi conditions while interacting with rhizobia (Fig 6a and Tables S3). In contrast, 633 (331 up-regulated and 302 down-regulated) and 149 (105 up-regulated and 44 down-regulated) genes were uniquely regulated in Pi-optimal and Pi-deficient seedlings, respectively (Figure 6b and Tables S4-S5).

Further hierarchical clustering analyses on the 234 common regulated genes revealed a clear variation in the expression levels computed for these genes (Fig 6 c-d). For instances, we identified two clusters showing obvious differences when comparing the expression levels computed for both Pi-optimal and Pi-deficient

seedlings inoculated with rhizobia (Figure 6c). The first identified cluster (Cluster “I”) contains genes whose expression levels were higher in rhizobia-inoculated Pi-deficient seedlings than in rhizobia-inoculated optimal-Pi seedlings, whereas the second cluster (cluster “II”) contains genes whose expression levels were higher in optimal-Pi seedlings than in Pi-deficient seedlings, both of them inoculated with rhizobia (Fig 6c). To extend this analysis and identify genes differentially regulated between Pi-optimal and Pi-deficient seedlings while interacting with rhizobia, we perform a pair-wise comparison of the expression levels between rhizobia-inoculated optimal-Pi and rhizobia-inoculated Pi-deficient conditions. This comparison led us to the identification of 131 differentially expressed genes (77 showing higher expression in Pi-deficient seedlings and 54 showing higher expression in control seedlings) (Fig S3 and Table S6). The observed variation in the expression of these 131 genes was on average by five-fold. For instance, Phvul.001G226900 and Phvul.008G244400, which encode for a Wall-associated receptor kinase galacturonan-binding protein and Leucine-Rich Repeat Protein Kinase-Like protein, respectively, showed on average by a four-fold increase in control common bean seedlings. In contrast, the genes Phvul.001G228500 and Phvul.011G074400, which encode for a U-Box domain-containing protein and Fasciclin-Like Arabinogalactan Protein11, respectively, showed on average by a six-fold increase in Pi-deficient common seedlings. Collectively, this transcriptional data clearly indicate that Pi deficiency affects the activity of different rhizobia-regulated genes by either inactivating, decreasing or increasing their expression in common bean.

3.6. Expression of hormone- and signal-transduction-related genes is compromised in rhizobia inoculated Pi-deficient common bean plants

To gain more insights into the molecular functions of the differentially regulated genes identified in this study, we performed a gene enrichment analysis and a functional classification in MapMan to identify the molecular mechanisms leading to an inefficient symbiosis between common bean and rhizobia under Pi-deficient conditions. This analysis indicated that “Regulation of transcription”, “Hormones”, “Regulation/Signal transduction”, “Transport”, “Biotic interactions” and “Protein modification/degradation” were the most overrepresented functional categories in both control and Pi-deficient common bean seedlings interacting with rhizobia (Fig. 7).

Phytohormones play a critical role in different stages of the symbiosis between legumes and rhizobia [85]. For instances, it has been demonstrated that both auxin and cytokinin positively regulate the expression of genes that conforms the common symbiosis pathway, as well as the progression of the symbiotic signaling events from the epidermis to the cortex [27, 86]. Recently, it was demonstrated that the auxin accumulation in the root hairs upon rhizobia

recognition is essential for the infection thread formation [10]. Furthermore, it has also been demonstrated that the correct perception of cytokinin is crucial for the polar auxin transport and the subsequent auxin accumulation in the rhizobia-infected root hairs [87].

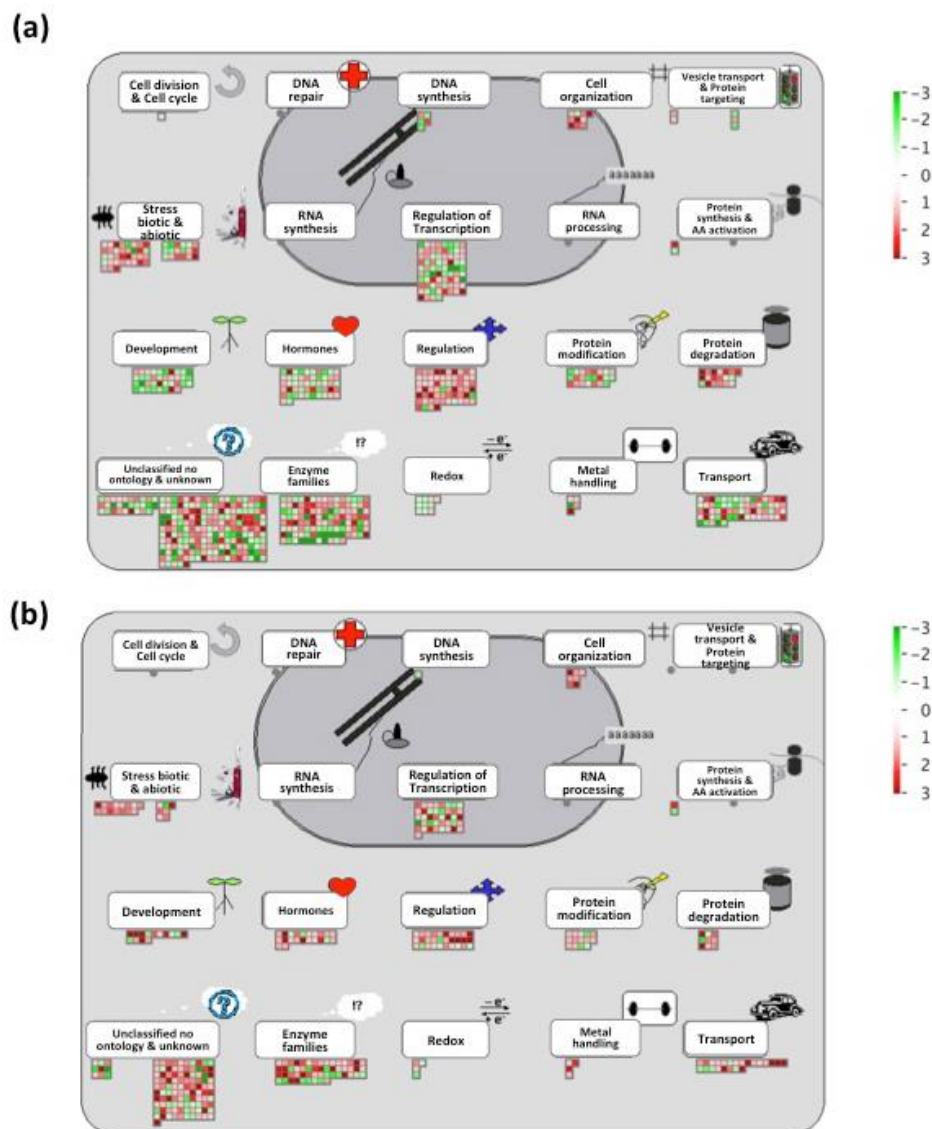


Figure 7: Functional categories affected in Pi-deficient common seedlings inoculated with rhizobia

MapMan regulation overview map showing differences in transcript levels between common bean seedlings growing under optimal-Pi (OP) (a) or low-Pi (LP) (b) conditions and inoculated for 48 hours with rhizobia. Fold-changes were false-colored; genes showing higher expression are shown in different scales of red color, whereas genes showing lower expression were colored in green color. The complete sets of genes submitted to MapMan analysis are shown in Tables S2 and S3.

Based on the fact that auxin and cytokinin are crucial regulators of both early and late (e.g., nodule development) stages of the symbiosis between legume and rhizobia [88], and the fact that we found that the “Hormones” category was one of the overrepresented functional categories, we sought in our transcriptomic data to determinate whether the expression of genes related to these two hormones was affected by Pi deficiency. This analysis revealed that twelve auxin-related genes (six of them involved in auxin biosynthesis, one gene involved in auxin homeostasis and five auxin-responsive genes) and eight cytokinin-related genes (five of them involved in cytokinin homeostasis, two involved in cytokinin biosynthesis, and one involved in cytokinin signaling) were differentially regulated in optimal-Pi common bean seedlings and inoculated with rhizobia (Fig 8a-b). In contrast, only four auxin-related genes (two of them involved in auxin biosynthesis, one involved in auxin homeostasis, and one auxin-responsive gene) and one cytokinin-related (cytokinin homeostasis) gene were differentially regulated in response to rhizobia when common bean seedlings were grown under Pi-deficient condition (Fig. 8). The fact that Pi deficiency affects the expression of auxin- and cytokinin-related genes in response to rhizobia, lead us to propose that the defects in early molecular (e.g., expression of *PvNIN* and *PvFLOT2*) and physiological (e.g., root hair deformation) events observed in Pi-deficient common bean seedlings might be partially explained by defects in the auxin-cytokinin balance.

In addition to auxin- and cytokinin-related genes, we also found that genes involved in the biosynthesis of the phytohormones ethylene, abscisic acid (ABA)- and jasmonate, as well as in the signal transduction related to these three phytohormones, were differentially regulated in response to rhizobia inoculation. Although we observed that common bean seedlings growing under optimal-Pi conditions and inoculated with rhizobia showed more differentially regulated genes (six ABA-related genes, seven ethylene-related genes, and six jasmonate-related genes) related to these three hormones than Pi-deficient seedlings inoculated with rhizobia, the majority of them were down-regulated (Fig 9). In contrast, all ethylene-, ABA- and jasmonate-related genes identified in common bean seedlings grown under Pi-deficient conditions and inoculated with rhizobia were up-regulated (Fig 9).

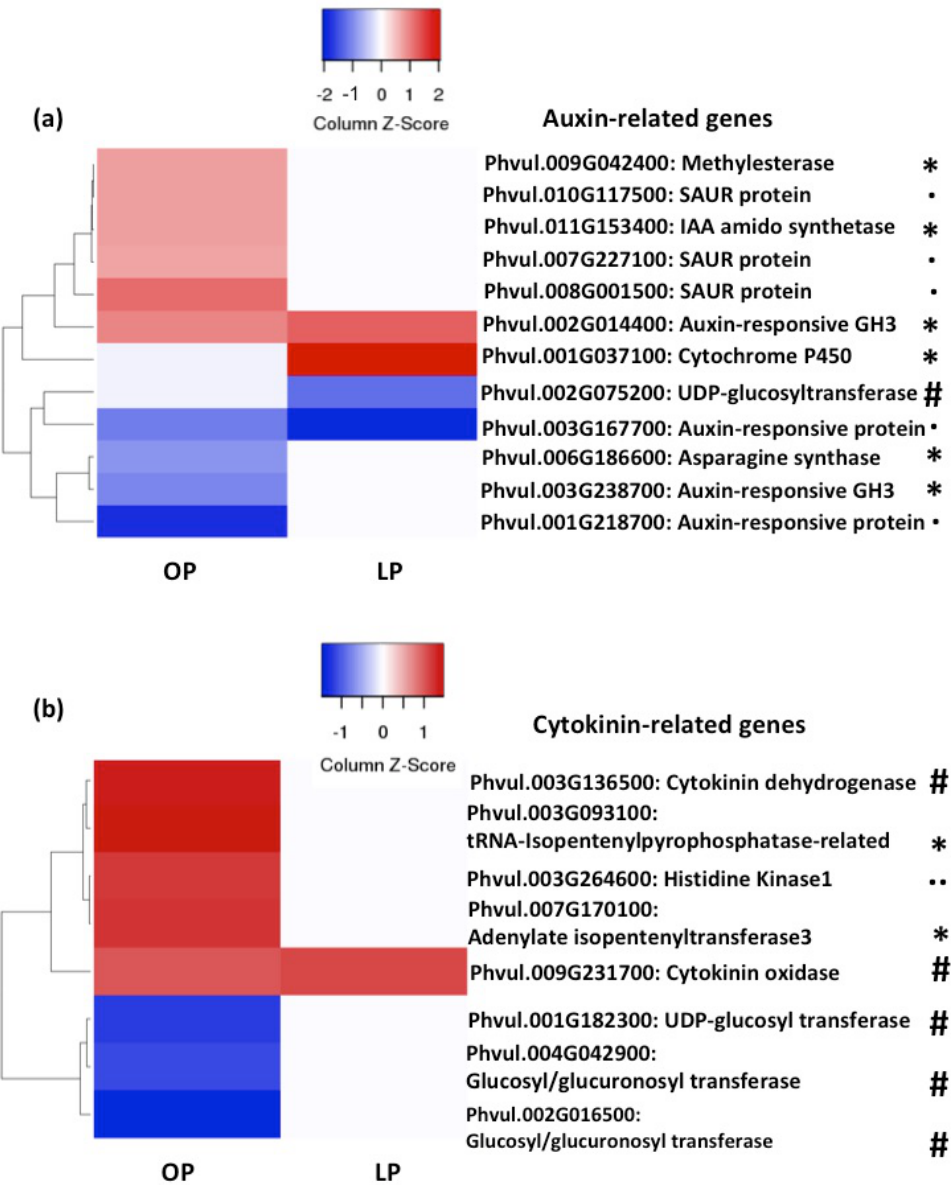


Figure 8: Pi deficiency affects the expression of rhizobia-induced auxin- and cytokinin-related genes

Heat-map showing the fold-change of genes involved in the biosynthesis (*), homeostasis (#), signal transduction (..) of auxin (a) or cytokinin (b) in common bean seedlings growing under optimal-Pi (OP) or low-Pi (LP) conditions and inoculated for 48 hours with rhizobia. Genes regulated by auxins or cytokinin are indicated with a dot. Fold-changes were false-colored. Genes showing higher expression are shown in different scales of red color, whereas genes showing lower expression were colored in blue color. Genes involved in biosynthesis.

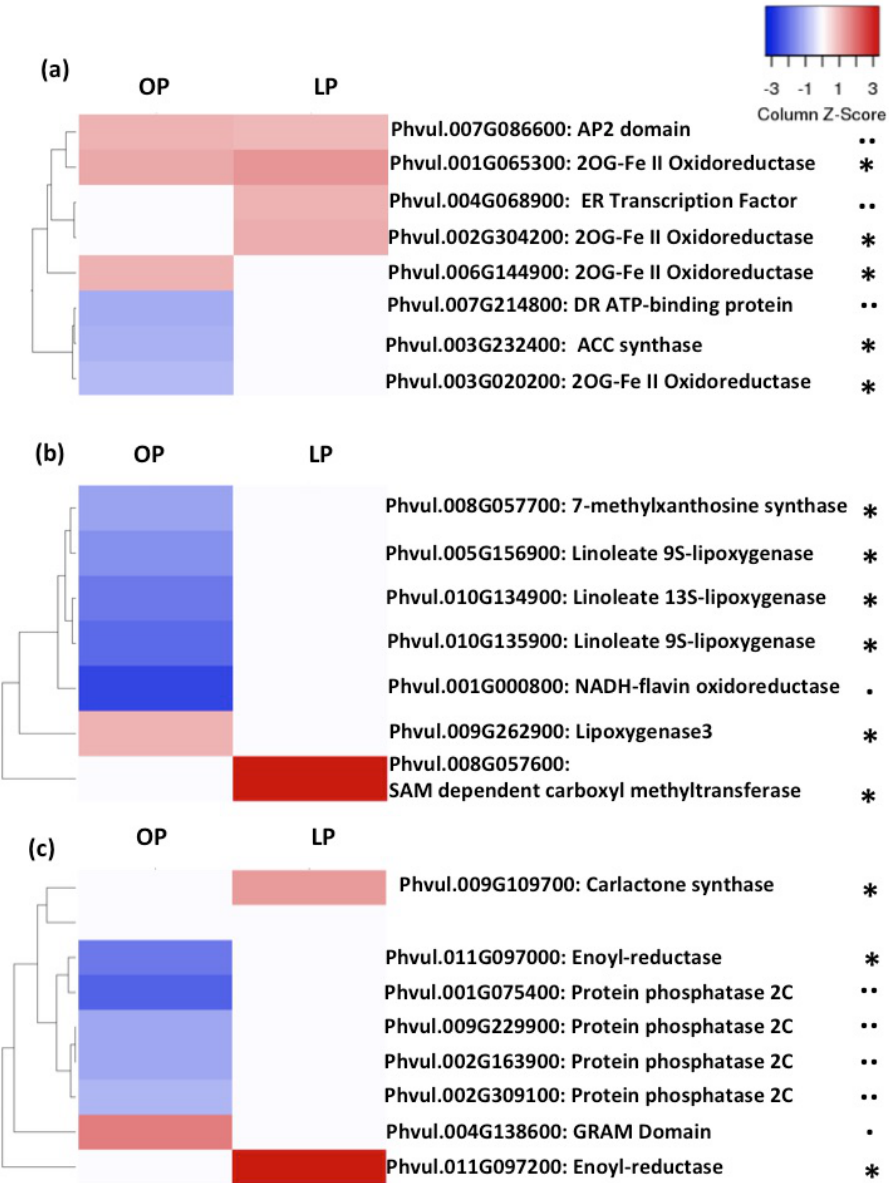


Figure 9: Pi deficiency induce the expression of ethylene-, jasmonate-, and abscisic acid-related genes

Heat-map showing the fold-change of genes involved in the biosynthesis (*), homeostasis (#), signal transduction (..) of ethylene (a), jasmonate (b) or abscisic acid (c) in common bean seedlings growing under optimal-Pi (OP) or low-Pi (LP) conditions and inoculated for 48 hours with rhizobia. Genes regulated by ethylene, jasmonate or abscisic acid are indicated with a dot. Fold-changes were false-colored. Genes showing higher expression are shown in different scales of red color, whereas genes showing lower expression were colored in blue color.

Ethylene, jasmonate, and ABA are essential to activate a series of molecular and physiological responses allowing plants to cope with Pi deficiency [89].

However, growing evidence indicates that these three phytohormones negatively control the establishment of the root nodule symbiosis [90-92]. For instances, it has been demonstrated that the accumulation of ethylene or jasmonate inactivates the expression of early symbiosis-related genes (e.g. *ENOD11*), inhibits the initiation and maintenance of the calcium spiking, decreases the number of rhizobia-induced root hair deformation and infection thread, and reduces nodule formation in *M. truncatula* plants [90-91]. Recently, it was demonstrated that the negative impact of ethylene on the rhizobia infection process and nodule formation is under the control of the regulator EIN2 [28]. Hence, our transcriptional data suggest that the activation of genes related to the biosynthesis and signal transduction of these three phytohormones is required in order to allow common bean to properly adapt to Pi deficiency. However, the activation of the ethylene-, jasmonate- and ABA signaling pathways compromise the activation of early molecular and physiological events of the root nodule symbiosis, as we demonstrated in this study.

The proper recognition of rhizobia by the host legume is crucial for a successful symbiosis. To this end, legumes rely on the LysM-domain receptor kinases NFR5 [93], NFR1 [94] and eNFR [7], as well as in the LRR receptor-like kinase SYMRK, to properly detect and decode the NF signal [15-16]. Recently, it was demonstrated that a fourth LysM receptor kinase receptor, EPR3, is required for the perception of compatible rhizobial exopolysaccharides and promotes a successful infection and colonization [95]. Additionally, based on the fact that a gene encoding a cell wall-associated receptor kinases (WAKs) is significantly up-regulated upon one-hour treatment with NF in *M. truncatula* roots, it has been proposed that WAKs might play a critical role in the early steps of this symbiosis, primarily in the cell wall-cytoplasm signaling [96]. In our transcriptomic analysis, we also found different types of protein receptors, including LysM receptor kinases, LRR receptor kinases, and WAKs, that were differentially regulated in both control and Pi-deficient seedlings inoculated with rhizobia. However, we observed that Pi-deficient seedlings inoculated with rhizobia showed less differentially regulated genes encoding for protein receptors in response to rhizobia (Fig S4). These data suggest that the misregulation of the expression of additional protein receptor might contribute to an inefficient communication between common bean and rhizobia under Pi-limiting conditions.

5. Conclusions

The data presented in this study lead us to conclude that Pi deficiency negatively affects early events of the symbiosis between legumes and rhizobia. The negative effects in the symbiosis between common bean and rhizobia under Pi deficiency might be triggered by an imbalance between auxin and cytokinin, as well as by the activation of the ethylene, jasmonate and ABA-related signaling pathway, which are negative regulators of early molecular events of this symbiosis. Finally, the reduction in the number of nodules observed under Pi-deficient conditions can be also explained by a constitutive activation of the AON process; however, further experimentation is needed to confirm this hypothesis.

Supplementary Materials: The following materials are available online at www.mdpi.com

Table S1: Primer sequences used for qRT-PCR analysis

Table S2: Rhizobia-induced genes under optimal-Pi conditions

Table S3: Rhizobia-induced genes under low-Pi conditions

Table S4: Commonly regulated genes in both optimal- and low-Pi conditions

Table S5: Genes uniquely regulated under optimal-Pi conditions

Table S6: Genes uniquely regulated under low-Pi conditions

Table S7: Expressional behavior of rhizobia-induced genes in both optimal- and low-phosphate conditions

Figure S1: *In vitro* system to assess early responses to rhizobia on Pi-deficient common bean seedlings. Seedlings were grown under optimal-Pi (OP) (a) or low-Pi (LP) (b) conditions. Seedlings growing under LP conditions show a 50% decrease in their Pi content (c). Asterisk indicates a significant difference according to One-way ANOVA (p -value<0.001).

Figure S2: qRT-PCR validation of the mRNA-seq datasets. Data showed are the fold-change obtained from the pairwise comparison between the expression levels obtained from seedlings grown under optimal-Pi (OP) or low-Pi (LP) inoculated with rhizobia (R; OPR or LPR) or mock (M; OPM or LPM).

Figure S3: Genes showing significantly higher expression levels in Pi-deficient common seedlings inoculated with rhizobia. Data showed are the expression levels obtained from common bean seedlings grown under optimal-Pi (OP) or low-Pi (LP) conditions and inoculated with rhizobia. Panels on the right site show the functional categories regulated under the described experimental conditions.

Figure S4: Expression pattern of Protein receptors- and secondary metabolism-related genes. Data showed are the fold-change obtained from the pairwise comparison between the expression levels obtained from seedlings grown under optimal-Pi (OP) or low-Pi (LP) inoculated with rhizobia (R; OPR or LPR) or mock (M; OPM or LPM). Fold-changes were false-colored; genes showing higher

expression are shown in different scales of red color, whereas genes showing lower expression were colored in green color.

Author Contributions: O.V.-L. and M.L. proposed and designed the study. M.C.I.-A. and L.G. generated the *R. tropici*::GUS strain. M.C. I.-A., M.d. R. R.-S. and M. d. S.S.-C analyzed the rhizobia-induced root hair deformation. M. C. I.-A analyzed the infection thread formation. M.C. I. -A and M.d. R. R.-S., analyzed the expression symbiosis-related genes. M.C.I.-A., M.d. R. R.-S., M. d. S. S.-C., D.G.M.-C, and N. A. C. -G. generated biological material for mRNAseq analysis. S.S., T.J., L. P., O.V.-L., and M.C.I-A. analyzed the mRNAseq data. O.V.-L., M.L., M.C.I-A. wrote the manuscript. All authors read and approved the manuscript.

Funding: This research was supported by a grant from Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT grant #IN213017) to OVL. This work was also supported by the United States National Sciences Foundation grant number IOS-1339194 and IOS-1453613 to ML. Mariel C. Isidra-Arellano is a Doctoral student from Programa de Doctorado en Ciencias Biológicas, Universidad Nacional Autónoma de México (UNAM) and receive a fellowship from Consejo Nacional de Ciencia y Tecnología (CONACyT, CVU: 919676). Maria del Rocio Reyero-Saavdra is a Doctoral student from Programa de Doctorado en Ciencias Biomédicas, Universidad Nacional Autónoma de México (UNAM) and receive a fellowship from CONACyT (347027/239879).

Acknowledgments: We thank the Joint Genome Institute for prepublication access to the *Phaseolus vulgaris* V2.1 genome sequence. High-throughput services were performed at the University of Missouri DNA Core Facility. We would like to thank Dr. Jose L. Reyes (Instituto de Biotecnología UNAM), Dr. Georgina Hernandez (Centro de Ciencias Genómicas, UNAM) and Dr. Kiwamu Tanaka (Washington State University, Pullman, USA) for constructive discussion.

Conflicts of interest: Authors have no conflict of interests to declare

References

1. Castro-Guerrero, N.A.; Isidra-Arellano, M.C.; Mendoza-Cozatl, D.M.; Valdés-López, O. Common bean: A legume model on the rise for unraveling adaptations to iron, zinc and phosphate deficiencies. *Front. Plant Sci.* **2016**, *7*, 600, Doi: 10.3389/fpls.2016.00600.
2. Blair, M.W.; Izquierdo, P.; Astudillo, C.; Grusak, M.A. A legume biofortification quandary: variability and genetic control of seed coat micronutrient accumulation in common beans. *Front. Plant Sci.* **2013**, *4*, 275, Doi:10.3389/fpls.2013.00275.
3. Jha, A.B.; Ashokkumar, K.; Diapari, M.; Ambrose, S. J.; Zhang, H.; Tar'an, B.; Bett, K.E; Vandenberg, A.; Warkentin, T.D.; et al. Genetic diversity of folate profiles in seeds of common bean, lentil, chickpea and pea. *J. Food Composit. Anal.* **2015**, *42*, 134–140, Doi.org/10.1016/j.jfca.2015.03.006.
4. Peters, N.K.; Frost, J.N.; Long, S.R. A plant flavonone, loteolin, induces expression of *Rhizobium meliloti* genes. *Sciences.* **1996**, *233*, 977-980.
5. Liu, C.W.; Murray, J. The role of flavonoids in nodulation host-range specificity and update. *Plants.* **2016**, *5*, 33, Doi: 10.3390/plants5030033.
6. Broghanmer, A.; Krusell, L.; Blaise, M.; Sauer, J.; Sullivan, J. T.; Maolanon, N.; Vinther, M.; Lorentzen, A.; Madsen E. B.; Jensen, K. J.; et al. Legume receptors perceive the rhizobial lipochitin oligosaccharide signal molecules by direct binding. *Proc Natl Acad Sci U.S.A.* **2012**, *109*, 13859-1864, Doi: 10.1073/pnas.1205171109.
7. Murakami, E.; Cheng, J.; Gysel, K.; Bozsoki, Z.; Kawaharada, Y.; Hjuler, C. T.; Sørensen, K.K.; Tao K.; Kelly, S.; Venice, F.; et al. Epidermal LysM receptor ensure robust symbiotic signalling in *Lotus japonicus*. *eLife.* **2018**, *7*, e33506, Doi: 10.7554/eLife.33506.
8. Venkateshwaran, M.; Volkening, J.D.; Sussman, M.R.; Ané, J.M. Symbiosis and the social network of higher plants. *Curr. Opin. Plant Biol.* **2013**, *16*, 118–127, Doi: 10.1016/j.pbi.2012.11.007.
9. Lei, M. J.; Wang, Q.; Li, X.; Chen, A.; Luo, L.; Xie, Y.; Li G.; Luo D.; Mysore K.S.; Wen J.; et al. The small GTPase ROP10 of *Medicago truncatula* is required for both tip growth of root hairs and Nod Factor-induced root hair deformation. *Plant Cell.* **2015**, *27*, 806-822, Doi: 10.1105/tpc.114.135210.
10. Nadzieja, M.; Kelly, S.; Stougaard, J.; Reid, D. Epidermal auxin biosynthesis facilitates rhizobial infection in *Lotus japonicus*. *Plant J.* **2018**, *95*, 101-111, Doi: 10.1111/tpj.13934.
11. Fournier, J.; Timmers, A. C. J.; Sieberer, B. J.; Jauneau, A.; Chabaud, M.; Barker, D. G. Mechanism of infection thread elongation in root hairs of *Medicago truncatula* and dynamic interplay with associated rhizobial colonization. *Plant Physiol.* **2008**, *148*, 1985-1995, Doi: 10.1104/pp.108.125674.

12. Fournier, J.; Teillet, A.; Chabaud, M.; Ivanov, S.; Genre, A.; Limpens, E.; de Carvalho-Nievel, F.; Barker, D. Remodeling of the infection chamber before infection thread formation reveals a two-step mechanism for rhizobial entry into the host legume root hair. *Plant Physiol.* **2015**, *167*, 1233–1242, Doi: 10.1104/pp.114.253302.
13. Xiao, T.T.; Schilderink, S.; Moling, S.; Deinum, E.E.; Kondorosi, E.; Franssen, H.; Kulikova, O.; Niebel, A.; Bisseling, T. Fate map of *Medicago truncatula* root nodules. *Development.* **2014**, *141*, 3517–3528, Doi: 10.1242/dev.110775.
14. Genre, A.; Russo, G. Does a common pathway transduce symbiotic signals in plant-microbe interactions?. *Front. Plant Sci.* **2016**, *7*, 96, Doi: 10.3389/fpls.2016.00096.
15. Bersoult, A.; Camut, S.; Perhald, A.; Kereszt, A.; Kiss, G.B.; Cullimore J.V. Expression of the *Medicago truncatula* DM12 gene suggests roles of the symbiotic nodulation receptor kinase in nodules and during early nodule development. *Mol Plant Microbe Interact.* **2005**, *18*, 869–876, Doi: 10.1094/MPMI-18-0869.
16. Hogg, B. V.; Cullimore, J. V.; Ranjeva, R.; Bono, J. J. The DMI1 and DMI2 early symbiotic genes of *Medicago truncatula* are required for a high-affinity nodulation factor-binding site associate to a particulate fraction of roots. *Plant Physiol.* **2006**, *140*, 365–373, Doi: 10.1104/pp.105.068981.
17. Imaizumi-Anraku, H.; Takeda, N.; Charpentier, M.; Perry, J.; Miwa, H.; Umehara, Y.; Kouchi, H.; Murakami, Y.; Mulder, L.; Vickers, K.; et al. Plastid proteins crucial for symbiotic fungal and bacterial entry into plant host. *Nature.* **2005**, *433*, 527–531, Doi: 10.1038/nature03237.
18. Kanamori, N.; Madsen, L. H.; Radatoiu, S.; Frantescu, M.; Quistgaard, E. M.; Miwa, H.; et al. A nucleoporin is required for induction of Ca²⁺ spiking in legume nodule development and essential for rhizobial and fungal symbiosis. *Proc Natl Acad Sci U.S.A.* **2006**, *103*, 359–364, doi: 10.1073/pnas.0508883103.
19. Saito, K.; Yoshikawa, M.; Yano, K.; Miwa, H.; Uchida, H.; Asamizu, E.; Sato, S.; Tabata, S.; Imaizumi-Anraku, H.; Kouchi, H. et al. NUCLEOPORIN85 is required for calcium spiking, fungal and bacterial symbioses, and seed production in *Lotus japonicus*. *Plant Cell.* **2007**, *19*, 610–624, doi: 10.1105/tpc.106.046938.
20. Groth, M.; Takeda, N.; Perry, J.; Uchida, H.; Dräxl, S.; Brachmann, A.; Sato, S.; Tabata, S.; Kawaguchi, M.; Wang T.L.; et al. NENA, a *Lotus japonicus* homolog of Sec13, is required for rhizodermal infection by arbuscular mycorrhiza fungi and rhizobia but dispensable for cortical endosymbiotic development. *Plant Cell*, **2010**, *22*, 2509–2526, doi: 10.1105/tpc.109.069807.
21. Charpentier, M.; Sun, J.; Vaz Martins, T.; Radhakrishnan, G.V.; Findlay, K.; Soumpourou, E.; Thouin, J.; Véry, A.A.; Sanders, D.; Morris, R.J.; et al. Nuclear-

- localized cyclic nucleotide-gated channels mediate symbiotic calcium oscillations. *Science*. **2016**, *352*, 1102–1105, Doi: 10.1126/science.aae0109.
22. Miller, J.B.; Pratap, A.; Miyahara, A.; Zhou, L.; Borneman, S.; Morris, R.J.; Oldroyd, G.E. Calcium/Calmodulin- dependent protein kinase is negatively and positively regulated by calcium, providing a mechanism for decoding calcium responses during symbiosis signaling. *Plant Cell*. **2013**, *25*, 5053–5066, doi: 10.1105/tpc.113.116921.
23. Singh, S.; Katzer, K.; Lambert, J.; Cerri, M.; Parniske, M. CYCLOPs, a DNA-binding transcriptional activator orchestrates symbiotic root nodule development. *Cell Host Microbe*. **2014**, *15*, 139–152, Doi: 10.1016/j.chom.2014.01.011.
24. Hirsch, S.; Kim, J.; Muñoz, A.; Heckmann, A.B.; Downie, J.A.; Oldroyd, G.E.D. GRAS proteins form a DNA binding complex to induce gene expression during nodulation signaling in *Medicago truncatula*. *Plant Cell*. **2009**, *21*, 545–557, Doi: 10.1105/tpc.108.064501.
25. Soyano, T.; Kouchi, H.; Hirota, A.; Hayashi, M. Nodule Inception directly targets *NF-Y* sub-unit genes to regulate essential processes of root nodule development in *Lotus japonicus*. *PLoS Genet*. **2013**, *9*, e1003352, Doi: 10.1371/journal.pgen.1003352.
26. Haney, C.H.; Long, S.R. Plant flotillins are required for infection by nitrogen-fixing bacteria. *Proc. Natl. Acad. Sci.* **2010**, *107*, 478–483, Doi: 10.1073/pnas.0910081107.
27. van Zeijl, A.; Op den Camp, R.H.M.; Deinum, E.E.; Charnikhova, T.; Franssen, H.; Op den Camp, H.J.M.; Bouwmeester, H.; Kohlen, W.; Bisseling, T.; Geurts, R. Rhizobium lipo-chitoooligosaccharide signaling triggers accumulation of cytokinins in *Medicago truncatula* roots. *Mol Plant*. **2015**, *8*, 1213–1226, Doi: 10.1016/j.molp.2015.03.010.
28. Reid, D.; Liu, H.; Kelly, S.; Kawaharada, Y.; Mun, T.; Andersen, S. U.; Desbrosses, G.; Stougaard, J. Dynamics of Ethylene production in response to compatible Nod Factor. *Plant Physiol.* **2018**, *176*, 1764–1772, Doi: 10.1104/pp.17.01371.
29. Penmetsa, V. R.; Cook, D. R. A legume ethylene-insensitive mutant hyperinfected by its rhizobial symbiont. *Science*. **1997**, *275*, 527– 530, Doi: 10.1126/science.275.5299.527.
30. Trichine, L.; Sandal, N.; Madsen, L. H.; Radutoiu, S.; Albrechtsen, A. S.; Sato, S.; Asamizu, E.; Tabata, S.; Stougaard, J. A gain-of-function mutation in a cytokinin receptor triggers spontaneous root nodule organogenesis. *Science*. **2007**, *315*, 104–107, Doi: 10.1126/science.1132397.
31. Ferguson, B. J.; Mens, C.; Hastwell, A., H.; Zhang, M.; Su, H.; Jones, C.H.; Chu, X.; Gresshoff, P.M. Legume nodulation: The host controls the party. *Plant Cell Environ.* **2018**, *1*, 11, Doi: 10.1111/pce.13348.

32. Ferguson, B. J.; Dongxue, L.; Hastwell, A. H.; Reid, D. E.; Li, Y.; Jackson, S. A.; Gresshoff, P. The soybean (*Glycine max*) nodulation-suppressive CLE peptide, GmRIC1, functions interspecifically in common white bean (*Phaseolus vulgaris*), but not in a supernodulating line mutated in the receptor PvNARK. *Plant Biotechnol J*, **2014**, *12*, 1085-1097, Doi: 10.1111/pbi.12216.
33. Krusell, L.; Madsen, L. H.; Sato, S.; Aubert, G.; Genua, A.; Szczyglowski, K.; et al. Shoot control of root development and nodulation is mediated by a receptor-like kinase. *Nature*. **2002**, *420*, 422-426, Doi:10.1038/nature01207.
34. Nishimura, R.; Hayashi, M.; Wu, G.J.; Kouchi, H.; Imaizumi-Anraku, H.; Murakami, Y.; Kawasaki, S.; Akao, S.; Ohmori, M.; Nagasawa, M.; et al. HAR1 mediates systemic regulation of symbiotic organ development. *Nature*. **2002**, *420*, 426-429, Doi: 10.1038/nature01231.
35. Searle, I. R.; Men, A. E.; Laniya, T. S.; Buzas, D. M.; Iturbe-Ormaetxe, I.; Carroll, B. J.; Gresshoff, P. M. Long-distance signaling in nodulation directed by a CLAVATA1-like receptor kinase. *Science*. **2003**, *299*, 109-112, Doi: 10.1126/science.1077937.
36. Schnabel, E.; Journet, E. P.; de Carvalho-Niebel, F.; Duc, G.; Frugoli, J. The *Medicago truncatula* SUNN gene encodes a CLV1-like leucine-rich repeat receptor kinase that regulates nodule number and root length. *Plant Mol Biol*. **2005**, *58*, 809-822, doi: 10.1007/s11103-005-8102-y.
37. Broughton, W. J.; Hernandez, G.; Blair, M.; Beebe, S.; Gepts, P.; Vanderleyden, J. Beans (*Phaseolus spp.*) - model food legumes. *Plant Soil*. **2003**, *252*, 55-128, Doi:10.1023/A:1024146710611.
38. Valdés-López, O.; Hernández, G. Transcriptional regulation and signaling in phosphorus starvation: what about legumes? *J Integr Plant Biol*. **2008**, *50*, 1213-1222, Doi: 10.1111/j.1744-7909.2008.00758.x.
39. Vance, C. P.; Uhde-Stone, C.; Allan, D. L. Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. *New Phytologist*. **2003**, *157*, 423-447, Doi: 10.1046/j.1469-8137.2003.00695.x.
40. Hernández, G.; Valdés-López, O.; Ramírez, M.; Goffard, N.; Weiller, G.; Aparicio-Fabre, R.; Fuentes, S. I.; Erban, A.; Kopka, J.; Udvardi, M. K.; et al. Global changes in the transcript and metabolic profiles during symbiotic nitrogen fixation in phosphorus-stressed common bean plants. *Plant Physiol*. **2009**, *151*, 1221-1238, Doi: 10.1104/pp.109.143842.
41. Hernandez, G.; Devron, J. J. Influence of oxygen and acetylene during in situ open-flow assays of nitrogenase activity (C₂H₂ reduction) in *Phaseolus vulgaris* root nodule. *Journal of Plant Physiology*. **1991**, *138*, 587-590, Doi:10.1016/S0176-1617(11)80246-4.

42. Vadez, V.; Rodier, F.; Payre, H.; Devon, J.J. Nodule conductance to O₂ and nitrogenase-linked respiration in bean genotypes varying in the tolerance of N₂ fixation to P deficiency. *Plant Physiology and Biochemistry*. **1996**, *34*, 871-878.
43. Cabeza, R.A.; Liese, R.; Lingner, A.; von Steieglitz, I.; Neumann, J.; Salinas-Riester, G.; Pommerenke, C.; Dittert, K.; Schulze, J. RNA-seq transcriptome profiling reveals that *Medicago truncatula* nodules acclimate N₂ fixation before emerging P deficiency reaches the nodules. *J Exp Bot*. **2014**, *65*, 6035-6048, Doi: 10.1093/jxb/eru341.
44. Chen, Z.; Cui, Q.; Liang, C.; Sun, L.; Tian, J.; Liao, H. Identification of differentially expressed proteins in soybean nodules under phosphorus deficiency through proteomics analysis. *Proteomics*. **2011**, *11*, 4648-4659, Doi: 10.1002/pmic.201100231.
45. Suleiman, S.; Ha, C. V.; Schulze, J.; Tran, L. S. P. Growth and nodulation of symbiotic *Medicago truncatula* at different levels of phosphorus availability. *J Exp Bot*. **2013**, *64*, 2701-2712, Doi: 10.1093/jxb/ert122.
46. Nasr Esfahani, M.; Inoue, K.; Chu, H. D.; Nguyen, K. H.; Van Ha, C.; Watanabe, Y.; Burritt, D.J.; Herrera-Estrella, L.; Mochida, K.; Tran, L.P. Comparative transcriptome analysis of nodules of two *Mesorhizobium*-chickpea associations with differential symbiotic efficiency under phosphate deficiency. *Plant J*. **2017**, *91*, 911-926, Doi: 10.1111/tpj.13616.
47. Sa T.; Israel D.W. Energy status and functioning of phosphorus-deficient soybean nodules. *Plant Physiol*. **1991**, *97*, 928-935, Doi: 10.1104/pp.97.3.928.
48. Al-Niemi, T.S.; Kahn, M.L.; McDermott, T.R. P metabolism in the bean-*Rhizobium tropici* symbiosis. *Plant Physiol*. **1997**, *113*, 1233-1242, Doi: 10.1104/pp.113.4.1233.
49. Vadez, V.; Beck, D. P.; Lasso, J. H.; Devron, J. J. Utilization of the acetylene reduction assay to screen for tolerance of symbiotic N₂ fixation to limiting P nutrition in common bean. *Physiol Plant*. **1997**, *99*, 227-232.
50. Tang, C.; Hinsinger, P.; Devron, J.J.; Jaillard B. Phosphorus deficiency impairs early nodule functioning and enhances proton release in roots of *Medicago truncatula* L. *Annals of Botany*. **2001**, *88*, 131-138, doi:10.1006/anbo.2001.1440.
51. Høgh-Jensen, H.; Schjoerring, J.K.; Soussana, J.F. The influence of phosphorus deficiency on growth and nitrogen fixation of white clover plants. *Annals of Bot*. **2002**, *90*, 745-753, Doi: 10.1093/aob/mcf260.
52. Schulze, J.; Temple, G.; Temple, S.; Beschow, H.; Vance, C.P. Nitrogen fixation by white lupin under phosphorus deficiency. *Ann Bot*. **2006**, *98*, 731-740, Doi: 10.1093/aob/mcl154.
53. Catoira, R.; Galera, C.; de Billy, F.; Penmetsa, R.V.; Journet, E.P.; Maillet, F.; Rosenberg, C.; Cood, D.; Gough, C.; Dénarié, J. Four genes of *Medicago truncatula*

- controlling components of a nod factor transduction pathway. *Plant Cell*. **2000**, *12*, 1647–1665, Doi:10.2307/3871180.
54. Dalla Via, V.; Narduzzi, C.; Aguilar, O. M.; Zanetti, M. E.; Blanco, A. Changes in the common bean transcriptome in response to secreted and surface signal molecules of *Rhizobium etli*. *Plant Physiol.* **2015**, *169*, 1356-1370, Doi: 10.1104/pp.15.00508.
55. Taussky, H.H.; Shorr, E. A microcolorimetric method for determination of inorganic phosphorus. *J Biol Chem.* **1953**, *202*, 675-685.
56. Reyero-Saavedra, M. D. R.; Qiao, Z.; Sánchez-Correa, M. D. S.; Díaz-Pineda, M. E.; Reyes, J. L.; Covarrubias, A.A.; Libault, M.; Valdés-López, O. Gene silencing of Argonaute5 negatively affects the establishment of the legume-rhizobia. *Genes (Basel)*. **2017**, *8*, E352, Doi: 10.3390/genes8120352.
57. Ramakers, C.; Ruijter, M. J.; Deprez, H. R.; Moorman, A.F. Assumption-free analysis of quantitative real-time polymerase chain reaction (PCR) data. *Neurosci Lett.* **2003**, *339*, 62-66, Doi:10.1016/S0304-3940(02)01423-4.
58. <http://bioinfo.ut.ee/primer3-0.4.0/primer3/>
59. Schmutz, J.; McClean, P. E.; Mamidi, S.; Wu, G.A.; Cannon, S.B.; Grimwood, J.; Chavarro, C.; Torres-Torres, M.; Geffroy, V.; Moghaddam, S.M.; et al. A reference genome for common bean and geno-wide analysis of dual domestications. *Nat Genet.* **2014**, *46*, 707-713, Doi: 10.1038/ng.3008.
60. https://phytozome.jgi.doe.gov/pz/portal.html#!info?alias=Org_Pvulgaris
61. <http://www.bioinformatics.babraham.ac.uk/projects/fastqc/>
62. http://www.bioinformatics.babraham.ac.uk/projects/trim_galore/
63. Langmead, B.; Salzberg, S.L. Fast Gapped-Read Alignment with Bowtie 2. *Nat Methods.* **2012**, *9*, 357-359, Doi: 10.1038/nmeth.1923.
64. Trapnell, C.; Pachter, L.; Salzberg, S. L. TopHat: discovering splice junctions with RNA-seq. *Bioinformatics.* **2009**, *25*, 1105-1111, Doi: 10.1093/bioinformatics/btp120.
65. Trapnell, C.; Roberts, A.; Goff, L.; Pertea, G.; Kim, D.; Kelley, D. R.; Pimentel, C.; Salzberg, S. L.; Rinn, J.; Pachter, L. Differential gene and transcript expression analysis of RNA-seq experiments with TopHat and Cufflinks. *Nat Prot.* **2012**, *7*, 562-578, Doi: 10.1038/nprot.2012.016.
66. Du, Z.; Zhou, X.; Liang, Y.; Zhang, Z.; Su, Z. agriGO: a GO analysis toolkit for the agricultural community. *Nucleic Acids Res.* **2010**, *38*, W64-W70, doi: 10.1093/nar/gkq310.
67. <http://bioinfo.cau.edu.cn>
68. Supek, F.; Bošnjak, M.; Škunca, N.; Šmuc, T. REVIGO summarizes and visualizes long list of gene ontology terms. *PLoS One.* **2011**, *6*, e21800, Doi: 10.1371/journal.pone.0021800.
69. <http://revigo.irb.hr>

70. Thimm, O.; Bläsing, O.; Gibon, Y.; Nagel, A.; Meyer, S.; Krüger, P.; et al. MAPMAN: a user-driven tool to display genomics data sets onto diagrams of metabolic pathways and other biological processes. *Plant J.* **2004**, *37*, 914-939, Doi: 10.1111/j.1365-313X.2004.02016.x.
71. Usadel, B.; Poree, F.; Nagel, A.; Lohse, M.; Czedik-Eysenberg, A.; & Stitt, M. A guide to using MapMan to visualize and compare Omics data in plants: a case study in the crop species, maize. *Plant Cell Environ.* **2009**, *32*, 1211-1229, Doi: 10.1111/j.1365-3040.2009.01978.x.
72. <https://mapman.gabipd.org>
73. Qiu, L.; Lin, J. S.; Xu, J.; Sato, S.; Parniske, M.; Wang, J.; Xie, F. SCARN a novel class of SCAR protein that is required for root-hair infection during legume nodulation. *PLoS Genet.* **2015**, *11*, e1005623, Doi: 10.1371/journal.pgen.1005623.
74. Cerri, M. R.; Frances, L.; Laloum, T.; Auriac, M. C.; Niebel, A.; Oldroyd, G. E.; Barke, D.G.; Fournier, J.; de Carvalho-Niebel, F. *Medicago truncatula* ERN transcription factors: regulatory interplay with NSP1/NSP2 GRAS factors and expression dynamics throughout rhizobia infection. *Plant Physiol.* **2012**, *160*, 2155-2172, Doi: 10.1104/pp.112.203190.
75. Howieson, J. G.; Robson, A. D.; Ewing, M. A. External phosphate and calcium concentrations and pH, but not the products of rhizobial nodulation genes, affects the attachment of *Rhizobium meliloti* to roots of annual medics. *Soil Biology and Biochemistry.* **1993**, *25*, 567-573, Doi: 10.1016/0038-0717(93)90195-H.
76. Hirsch, S.; Kim, J.; Muñoz, A.; Heckmann, A. B.; Downie, J. A.; Oldroyd, G. E. GRAS proteins from a DNA binding complex to induce gene expression during nodulation signaling in *Medicago truncatula*. *Plant Cell.* **2009**, *21*, 545-557.
77. Marsh, J.F.; Rakocevic, A.; Mitra, R.M.; Brocard, L.; Sun, J.; Eschstruth, A.; Long, S.; Schultze, M.; Ratet, P.; Oldroyd, G.E.D. *Medicago truncatula* NIN is essential for rhizobial-independent nodule organogenesis induced by autoactive calcium/calmodulin-dependent protein kinase. *Plant Physiol.* **2007**, *144*, 324-335, Doi: 10.1104/pp.106.093021.
78. Oldroyd, G. E.; Long, S. R. Identification and characterization of nodulation-signalling pathway 2, a gene of *Medicago truncatula* involved in Nod Factor signaling. *Plant Physiol.* **2003**, *131*, 1027-1032. Doi: 10.1104/pp.102.010710.
79. Reid, D. E.; Ferguson, B. J.; Gresshoff, P. M. Inoculation- and nitrate-induced CLE peptides of soybean control NARK-dependent Nodule formation. *Mol Plant Microbe Interact.* **2011**, *24*, 606-618. Doi: 10.1094/MPMI-09-10-0207.
80. Funayama-Noguchi, S.; Noguchi, K.; Yoshida, C.; Kawaguchi, M. Two CLE genes are induced by phosphate in roots of *Lotus japonicus*. *J Plant Res.* **2011**, *124*, 155-163, Doi: 10.1007/s10265-010-0342-5.
81. de Bang, T. C.; Lundquist, P. K.; Dai, X.; Boschiero, C.; Zhuang, Z.; Pant, P.; Torres-Jerez, I.; Roy, S.; Nogales, J.; Veerappan, V.; et al. Genome-Wide

- identification of *Medicago* peptides involved in macronutrient responses and nodulation. *Plant Physiol.* **2017**, *175*, 1669-1689, Doi: 10.1104/pp.17.01096.
82. Gutierrez-Alanis, D.; Yong, L.; Jiménez, P.; Alatorre-Cobos, F.; Oropeza-Aburto, A.; Mora-Macías, J.; Sánchez-Rodríguez, F.; Cruz-Ramírez, A.; Herrera-Estrella, L. Phosphate Starvation-Dependent Iron Mobilization Induces CLE14 Expression to Trigger Root Meristem Differentiation through CLV2/PEPR2 Signaling. *Dev Cell.* **2017**, *41*, 555-570, Doi: 10.1016/j.devcel.2017.05.009.
83. <https://www.ncbi.nlm.nih.gov/geo/>
84. Trapnell, C.; Hendrickson, D. G.; Sauvageau, M.; Goff, L.; Rinn, J. L.; Pachter, L. Differential analysis of gene regulation at transcript resolution with RNA-seq. *Nat Biotechnol.* **2013**, *31*, 46-53, Doi: 10.1038/nbt.2450.
85. Ferguson, B. J.; Mathesius, U. Phytohormone regulation of legume-rhizobia interactions. *J Chem Ecol.* **2014**, *40*, 770-790, Doi: 10.1007/s10886-014-0472-7.
86. Hirsch, A. M.; Bhuvaneswari, T. V.; Torrey, J. G.; Bisseling, T. Early nodulin genes are induced in alfalfa roots outgrowths elicited by auxin transport inhibitors. *Proc Natl Acad Sci U. S. A.* **1989**, *86*, 1244-1248, Doi: 10.1073/pnas.86.4.1244.
87. Ng, J. L.; Hassan, S.; Truong, T. T.; Hocart, C. H.; Laffont, C.; Frugier, F.; Mathesius, U. Flavonoids and auxin transport inhibitors rescue symbiotic nodulation in *Medicago truncatula* cytokinin perception *cre1*. *Plant Cell.* **2015**, *27*, 2210-2226.
88. Liu, H.; Zhang, C.; Yang, J.; Yu, N.; Wang, E. Hormone modulation of legume-rhizobial symbiosis. *J Integr Plant Biol.* **2018**, *60*, 632-648, Doi: 10.1093/mp/ssp120.
89. Rouached, H.; Arpat, A. B.; Poirier, Y. Regulation of phosphate starvation responses in plants: signaling players and cross-talks. *Mol Plant.* **2010**, *3*, 288-299.
90. Oldroyd, G. E. D.; Engstrom, E. M.; Long, S. R. Ethylene inhibits the Nod factor signaling transduction pathway of *Medicago truncatula*. *Plant Cell.* **2001**, *13*, 1835-1849, Doi: 10.1105/TPC.010193.
91. Sun, J.; Cardoza, V.; Mitchell, D. M.; Brighth, L.; Oldroyd, G.; Harris, J. M. Crosstalk between jasmonic acid, ethylene and Nod factor signaling allows integrations of diverse inputs for regulation of nodulation. *Plant J.* **2006**, *46*, 961-970, Doi: 10.1111/j.1365-313X.2006.02751.x
92. Ding, Y.; Kalo, P.; Yendrek, C.; Sun, J.; Liang, Y.; Marsh, J. F.; Harris, J. M.; Oldroyd, G. E. Absciscic acid coordinates Nod factors and cytokinins signaling during the regulation of nodulation in *Medicago truncatula*. *Plant Cell.* **2008**, *20*, 2681-2695, Doi: 10.1105/tpc.108.061739.
93. Madsen, E. B., Madsen, L. H., Radutoiu, S., Olbryt, M., Rakwalska, M., Szczyglowski, K., Sato, S.; Kaneko, T.; Tabata, S.; Sandal, N.; Stougaard, J. A receptor kinase gene of the LysM type is involved in legume perception of rhizobial signals. *Nature.* **2003**, *425*, 637-640, Doi: 10.1038/nature02045,

94. Radutoiu, S.; Madsen, L. H.; Madsen, E. B.; Felle, H. H.; Umehara, Y.; Sato, S.; Nakamura, Y.; Tabata, S.; Sandal, N.; Stougaard, J. Plant recognition of symbiotic bacteria requires two LysM receptor-like kinases. *Nature*. **2003**, *425*, 585-592.
95. Kwaharada, Y.; Kelly, S.; Nielsen, M. W.; Hjuler, C. T.; Gysel, K.; Muszynski, A.; Carlson, R. W.; Thygesen, M. B.; Sandal, N.; Asmussen, M. H.; et al. Receptor-mediated exopolysaccharide perception controls bacterial infection. *Nature*. **2015**, *523*, 308-312, Doi: 10.1038/nature14611.
96. Rose, C. M.; Venkateshwaran, M.; Volkening, J. D.; Grimsrud, P. A.; Maeda, J.; Park, K.; Howes-Podoll, M.; den Os, D.; Yeun, L. H.; Westphall, M. S.; et al. Rapid phosphoproteomic and transcriptomic changes in the rhizobia-legume symbiosis. *Mol Cell Proteomics*. **2012**, *11*, 724-744, Doi: 10.1074/mcp. M112.019208.