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Title: Systemic defense activation by COS-OGA in rice against root-knot nematodes depends on stimulation of the phenylpropanoid pathway

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Competing interests

Pierre Van Cutsem and Geraldine Van Aubel are co-inventors of a granted patent on the COS-OGA defense elicitor. They are employed by the company Fytofend, which commercializes COS-OGA based products. The other authors declare no competing interests. This research has not been financed by Fytofend.

Abstract

Activation of induced plant resistance to control pests and diseases is regaining attention in the current climate where chemical pesticides are being progressively banned. Formulations of chitosan oligomers (COS) and pectin□derived oligogalacturonides (OGA), COS-OGA, have previously been described to induce resistance against fungal diseases in different crop plants. Here, we investigated their potential and mode-of-action as preventive measures to control root-knot nematode *Meloidogyne graminicola* infection in rice.

The results show a significant reduction in root-galling and nematode development in rice plants that were treated through foliar application with the COS-OGA formulations FytoSol® and FytoSave® 24h before nematode inoculation. Hormone measurements, gene expression analyses, corroborated by treatments on salicylic acid (SA) and jasmonic acid (JA)-mutants indicated that the systemic COS-OGA induced defense mechanism against nematodes is not based on SA or JA activation. However, phenylalanine ammonia lyase (*PAL)* gene expression in roots as well as enzymatic PAL activity in the shoots were significantly induced 24 h after foliar COS-OGA spraying in comparison with untreated plants. COS-OGA-induced systemic defense was abolished in the rice *OsPAL4*-mutant, demonstrating that COS-OGA-induced defense is dependent on OsPAL4 activation in rice plants.

Keywords: plant defense elicitor, *Meloidogyne graminicola*, *Oryza sativa*, hormone, phenylpropanoids.

1. Introduction

With a world population that is currently growing at 83 million per year, the pressure on food production will only increase. Rice (*Oryza sativa*) is one of the most important staple foods in the world, with a production of more than 730 million tons per year (FAO, 2016). Although not well-known because they cause mainly belowground symptoms, plant parasitic nematode infections contribute to major agricultural losses in rice production (Mantelin et al., 2017). The root-knot nematode (RKN) *Meloidogyne graminicola* is probably the most damaging root pathogen affecting – mainly aerobic – rice fields in Asia, and it was recently also detected in Italian rice fields (Fanelli et al., 2017; Mantelin et al., 2017). RKN induce the formation of 'giant cells' inside the root tissue, from which they withdraw plant metabolites for their nutrition, leading to the visible formation of root-knots (galls) (Mantelin et al., 2017). The control of RKN using conventional methods is challenging because of their wide host range, ability to survive in soil and weeds, and the low inherent level of resistance in rice against this nematode. An alternative to use of nematicides, activation of the plant innate immunity could be a more environmentally friendly control method (Conrath et al., 2015).

Through evolutionary history, plants have acquired complex defense or 'immunity' mechanisms towards biotic stress factors like bacteria, fungi, insects and nematodes. Plant innate immunity is based on recognition of pathogen-associated molecular patterns (PAMPs), activating basal immune responses. Plant immune responses typically include rapid physiological changes such as Ca^{2+} uptake and production of reactive oxygen and nitrogen species (ROS and RNS). After signal transduction, these changes induce production of secondary metabolites, including hormones (among which salicylic acid (SA), jasmonic acid (JA), ethylene (ET), and abscisic acid (ABA)) and pathogenesis-related (PR) proteins. In case of PAMP-triggered immunity (PTI), the response is relatively small in magnitude but active against a broad range of pathogens (Jones & Dangl, 2006). The highly specific effector-

triggered immunity (ETI) - that is activated upon recognition of pathogen effectors - is much stronger and often accompanied by a hypersensitive response (HR) – induced cell death – at the site of attempted host colonization (Jones & Dangl, 2006).

Triggering a defensive state in a plant can be achieved by applying chemical or biological molecules or micro-organisms. Traditionally, the distinction is being made between SAR (systemic acquired resistance (SAR)) that depends on the plant hormone SA, and the SA-independent induced systemic resistance (ISR), which is based on JA/ET activation (Pieterse et al., 2014). Strong activation of plant immunity can be energy-consuming, but a more energy-efficient mechanism to trigger plant acquired immunity, known as priming, has been described in the early 2000's. During priming, a treatment, such as a (minor) stress or application of a certain molecular agent or micro-organism, puts a plant in a state of increased alertness with no or minimal direct immune gene induction or hormone accumulation, and hence no energy and yield loss. Upon pathogen attack, a faster and more robust defense response is activated in the primed plants than in unprimed plants (Conrath et al., 2015). In the dicotyledonous model plant *Arabidopsis thaliana*, priming has been shown to involve (1) the accumulation of dormant mitogen-activated protein kinases; and/or (2) epigenetic modifications; and/or (3) accumulation of secondary metabolites (Conrath et al., 2015). In our research we are evaluating the potential and mode of action of priming agents in the protection of rice against RKN. In previous research, we have identified the activity and involved pathways for priming agents, such as beta-amino butyric acid (BABA), and thiamine (Huang et al., 2016; Ji et al., 2015). Thiamine treatment leads to increases in H_2O_2 production in rice (Huang et al., 2016). Increases in H_2O_2 and callose as well as lignification were observed in nematode-infected plants pretreated with BABA (Ji et al., 2015). Lignin precursors are formed by the phenylpropanoid pathway, in which enzymatic conversion of phenylalanine into trans-cinnamate, mediated by phenylalanine ammonia lyase (PAL), is the

first and rate-limiting step. Next to monolignols, this plant-specific pathway, which is of significant importance to growth and development, can also convert phenylalanine into other secondary metabolites, such as flavonoids, salicylic acid, stilbenes and many other products playing a role in plant immunity (Vogt, 2010).

FytoSol and FytoSave are commercial formulations of a plant defense elicitor, commercialized by the company FytoFend. FytoSol and FytoSave contain chitosan oligomers (COS) combined with pectin□derived oligogalacturonides (OGA), aka COS-OGA. FytoSave (12.5 g/L COS-OGA) has been described to increase the resistance of Cucurbitaceae (cucumber, zucchini and melon), grapes and Solanaceae (tomato and sweet pepper) against powdery mildew (Van Aubel et al., 2014), through a mechanism relying on the induction of SA-related genes and proteins in tomato leaves (Van Aubel et al., 2016). FytoSave can also alleviate late blight caused by the oomycete *Phytophthora infestans* in potato, and this phenomenon is correlated with PR-gene activation (Clinckemaillie et al., 2017). FytoSol is a new composition still under development by the company FytoFend. Recently, FytoSol was shown to be even more effective at preventing late blight in potato under controlled conditions (Van Aubel et al., 2018). Although FytoSave strongly increased the SA content, it failed to induce sufficient protection against late blight, while FytoSol maintained or even decreased the free SA content in the presence of *P. infestans* and was more effective. In this manuscript, foliar application of FytoSave and FytoSol as potential activators of systemic defense was evaluated against root-knot nematodes in rice. By using hormone measurements, gene expression and biochemical analyses and rice mutants we investigated the involvement of the plant defense hormones SA and JA and of the phenylpropanoid pathway in COS-OGA induced root defense against RKN.

2. Materials & Methods

2.1. Plant material and growth conditions

Rice (*Oryza sativa*) seeds of cultivar Nipponbare were provided by U.S. Department of Agriculture (GSOR-100). Seeds of the *Ospal4*-mutant (Tonnessen et al., 2015) and its wild-type IR64 were kindly provided by the lab of J. Leach (Colorado State University, CO, USA). Seeds were germinated on wet filter paper in a petri dish for 4 days at 30°C. They were transplanted in in-house-made polyvinyl-chloride (PVC) tubes (height: 15 cm; diameter 3 cm) containing a mixture of fine sand and synthetic absorbent polymer (SAP) substrate (for more details see Nahar et al., 2011; Huang et al., 2015). The polymer used is Aquaperla® (DCM, Belgium). The plants were further kept in a growth room at 26°C, 12 h/12 h light regime (150 µmol/m^{2}s) and relative humidity of 70-75%. The plants were maintained by supplying 10 mL Hoagland solution three times a week. To avoid possible effects induced by the photoperiod, all inoculations and samplings were done at the same moment of the day, 10 am, which is 2h after sunrise.

2.2.Plant treatments

FytoSol and FytoSave (patent: US2015045221 (A1), US8871923B2) are commercial formulations containing 12.5 g/l oligosaccharide complex (chitosan fragments and pectin-derived fragments: COS-OGA; Van Aubel et al., 2018). In the first experiment the product was applied as foliar spray on 14-days-old rice plants, at different concentrations (1%, 0.5%, 0.25% and 0.125%, v/v) to evaluate the dose effect. In following experiments, the recommended dose of 0.5% was used, which corresponds to 62.5 ppm COS-OGA in the spray solution. In case of nematode infection experiments root inoculation was done 24 h after foliar treatment.

142 **2.3. Infection experiments**

143 *M. graminicola* - originally isolated in the Philippines (Batangas) - was kindly provided by
144 Prof. D. De Waele (Catholic University, Leuven, Belgium). The nematode culture was
145 maintained on susceptible rice plants grown in potting soil, under light and temperature
146 conditions as described above. About 3 months after inoculation, infected roots were cut into
147 1 mm pieces and nematodes (second stage juveniles, J2s) were extracted using a Baermann
148 funnel (Luc et al., 2005). The nematode suspension was collected 48 hrs later and
149 concentrated by centrifugation for 10 minutes at 1500 rpm at room temperature. Nematodes
150 were counted under light microscopy to estimate the number of nematodes in the suspension.

151 Fifteen-day-old rice plants were inoculated with 250 juveniles of *M. graminicola* or mock
152 inoculated with water. The infection level of the plants was evaluated at 14 days after
153 inoculation by counting the number of galls and nematodes per plant. Individual root systems
154 were removed from the substrate, gently washed and packed in a tissue bag (Miracloth,
155 VWR). They were stained with acid fuchsin, which leads to intense pink staining of the galls:
156 roots were boiled for 3 min in a solution of 0.8% acetic acid and 0.013% acid fuchsin.
157 Nematode development inside the galls as well as giant cells can be observed when the acid
158 fuchsin-stained root system is destained for approximately 4 d in acid glycerol. The
159 development of nematodes until maturity (females) is considered as a measure of general
160 nematode development in the root system. Galls and females were counted microscopically
161 using a stereomicroscope (Leica S8 APO, Leica Microsystems, Diegem, Belgium).

162 **2.4. Direct effect on nematodes**

163 Approximately 50 J2s were placed into a 2.5-cm diameter well on a 12-well culture plate
164 containing 1.5 ml of Fytosave or Fytosol at two different concentrations (1 and 0.5%) or 1.5

ml of distilled water for the mock treatment. The living and dead nematodes were counted at different time points under a stereomicroscope (Leica S8 APO, Leica Microsystems, Diegem, Belgium). Nematodes were considered dead if they were not moving and did not respond to being touched by a small probe. The experiment was performed three times with 6 replicates each.

2.5. RNA extraction, cDNA synthesis, and qRT-PCR

RNA was extracted using the Plant RNeasy Plant Mini kit (Qiagen) following the manufacturer's instructions. For each treatment, 3 biological replicates were taken, consisting of a pool of at least 4 plants. qRT-PCR was performed and analyzed as described in Huang et al.,2015. Expression levels were normalized using three reference genes, *OsEIF5C*, *OsEXP* and *OsEXPNarsai*. Primer pairs are listed in Huang et al., 2015 and Tonnessen et al., 2015.

2.6. Hormone measurements

For hormone measurement root and shoot tissues were collected and were homogenized using liquid N_2, and 100 mg of ground material was extracted at -80°C using the modified Bieleski solvent. After filtration (30 kDa Amicon® Ultra centrifugal filter unit), solvent evaporation and extract reconstitution, chromatographic separation was performed on a U-HPLC system (Thermo Fisher Scientific) with a Nucleodur C18 column (50 x 2 mm; 1.8 µm d_p). The detailed procedure is described in Haeck et al. (2018). For each treatment, 5 biological replicates, each consisting of a pool of at least 3 plants, were measured.

2.7. PAL-activity measurement

PAL-activity was measured as described in Camacho-Cristóbal et al., 2002. For each treatment, 4 biological replicates, each consisting of a pool of 3 plants, were sampled. From

each replicate, 100 mg of shoot or 100 mg of root samples were ground in liquid nitrogen and dissolved in 800 µl of 50 mM sodium phosphate as assay buffer containing 2% (w/v) poly-vinylpolypyrrolidone (PVPP), 2 mM EDTA, 18 mM-mercaptoethanol and 0.1% (v/v) Triton X-100. The homogenate was centrifuged at 7168 g, at 4□ for 10 mins. In different 2 ml tubes, 135 µl of reaction buffer, 50 µl of 5 mM of L-phenlyalanine, and 20 µl of supernatant were mixed. Absorbance was measured using a spectrophotometer at 290 nm. The reaction was started by incubating the samples in a water bath for 30 mins at 40□. To stop the reaction, 10 µl of hydrochloric acid was added and the sample was mixed for 10 mins, after which PAL activity was assayed by measuring the formation of trans-cinnamic acid at 290 nm. One unit (U) of PAL activity was defined as the amount of the enzyme that produced 1 nmol cinnamic acid per hour. Control assays had no L-phenylalanine as substrate.

2.8. Data collection and statistical analyses

All statistical analyses were performed in SPSS. Normality of the data was checked by applying the Kolmogorov-Smirnov test of normality ($\alpha = 0.05$). Homoscedasticity of the data was checked by applying the Levene test ($\alpha = 0.05$). Since the assumptions of normality and homoscedasticity of the data were found to be fulfilled in all cases, a Student's t-test or an ANOVA and Duncan's multiple mean comparison test were applied ($\alpha = 0.05$). In case of gene expression analysis, the REST2009-software, which is based on a data permutation test was used.

206 ## 3. Results

207 ### 3.1. Foliar COS-OGA treatment reduces the number of galls and female nematodes in
208 rice roots

209 In a first experiment, four different concentrations of COS-OGA (2 formulations: FytoSol
210 and FytoSave) were applied to rice plants to assess the effect on subsequent nematode
211 infection. Rice cv. Nipponbare roots were inoculated with *M. graminicola* 1 day after foliar
212 spraying with COS-OGA, and the numbers of galls and female nematodes were counted at 14
213 days post-inoculation (dpi). Compared with control plants, pre-treatment with all
214 concentrations and both formulations of COS-OGA resulted in a significantly lower number
215 of root galls per plant at 14 dpi (Fig. 1A). In addition, a significant decline in number of
216 females was observed in roots of pre-treated plants. At 14 dpi, the number of adult females in
217 the treated plants was significantly lower than in control plants, for all formulations and
218 dilutions except 0.125% FytoSol (Fig. 1B). The treatments did not have any negative effect
219 on visual plant appearance (data not shown) or plant growth, based on an evaluation of shoot
220 and root fresh weight at 14 dpi (Supplementary Figures 1A and 1B). COS-OGA is not
221 directly nematicidal, as no increased mortality was seen after nematode incubation even up to
222 7 days in 1% of FytoSol or FytoSave in comparison with water incubation (data not shown).
223 These data demonstrate that foliar COS-OGA treatment one day before inoculation not only
224 hinders root infection by *M. graminicola*, indicating that COS-OGA induces systemic
225 defense against *M. graminicola* in rice. Based on these data, it was decided to continue all
226 further experiments with the recommended dose of 0.5% COS-OGA.
227

3.2. COS-OGA induced defense acts independently of the major hormonal defense pathways salicylate and jasmonate

We hypothesized that COS-OGA might be activating the hormonal pathways involved in plant defense. Therefore, SA, JA, ABA and IAA levels were measured inside shoots (Figures 2A and 2B) and roots (Fig. 2C) of treated and untreated rice at 24 h after foliar application, which is the moment when nematodes are usually inoculated (although in this experiment the plants were not infected). Results presented in Figure 2A and 2B show that foliar application of both COS-OGA formulations resulted in decreased ABA and SA levels in the shoots at 24 h after treatment. FytoSave additionally led to significantly decreased JA levels in the shoots, a trend which was not significant for Fytosol treated plants. No significant changes in hormone levels were observed in the roots of treated rice plants at 24 h after treatment (Figure 2C), although JA levels were slightly but insignificantly increased and IAA levels decreased in roots of COS-OGA treated plants.

Gene expression analysis revealed only minor and very variable induction of the investigated defense genes in the shoot tissue at 24h post treatment with Fytosol (Fig. 3A). For Fytosave treatment, significant repression of *ICS1*, *PAL2*, *PAL4* and *PAL6* expression was observed in the shoots. In the root tissue, clear induction of many defense genes was seen (Fig. 3B). More specifically, both Fytosave and Fytosol induce the expression of *AOS2*, *PAL4*, *PAL6* and *PR1b* in the roots at 24 after foliar treatment. Similar trends were seen for *ICS1* and *PAL2*, although this was not statistically significant (Fig 3B).

The involvement of SA and JA in COS-OGA induced defense was further evaluated by investigating a set of mutants in the SA and JA-pathway: the SA-signaling deficient *WRKY45*-RNAi line, and JA biosynthesis mutant *hebiba*. Results, presented in Fig. 4, show that all three lines are more susceptible to RKN, as expected based on previously shown

252 importance of these genes for basal defense against RKN (Nahar et al., 2011; Ji et al., 2015).
253 However, COS-OGA systemic induced defense is still active in these three lines (Fig. 4A &
254 B), demonstrating that this phenomenon acts independently of SA-levels, SA-signaling and
255 JA biosynthesis.

256 **3.3. COS-OGA induced defense against nematodes activates PAL-activity in shoots and**
257 **is dependent on the *OsPAL4* gene**

258 Based on the above-described results, the typical defense hormones seem not to be
259 underlying COS-OGA-induced defense against RKN. However, gene induction did confirm
260 enhanced expression of multiple *PAL*-genes in the rice roots of treated plants. Therefore, we
261 decided to focus on the phenylpropanoid pathway, a well-known biosynthesis pathway for
262 several defense-related metabolites. PAL-activity was measured in root and shoots of the
263 treated plants at 24h after treatment. Data shown in Fig. 5A reveal significant induction of
264 PAL-activity in shoots of COS-OGA treated plants, both for FytoSave and FytoSol. No
265 increase in PAL-activity was seen in the roots (Fig. 5B).

266 To confirm the involvement of *OsPAL*-enhancement in COS-OGA induced defense, the
267 *OsPAL4*-mutant was used in an infection experiment. The wild-type line 'IR64', which
268 belongs to the subspecies 'indica', is slightly less responsive to FytoSol and FytoSave
269 treatment than the 'japonica' cultivars. 'Nipponbare' and 'Nihonmasari' (> 50% reduction,
270 Fig. 1A; Fig. 4B), although still a significant reduction in gall number was seen in treated
271 IR64-plants (33% reduction, Fig. 5C). It deserves also to be noted that a negative effect on
272 root length was observed in the COS-OGA treated 'IR64' rice plants (Supplementary Fig. 2).
273 Interestingly, the *OsPal4* mutant is not responding to COS-OGA treatments while wild-type
274 IR64 does (Fig. 5C). These data demonstrate that the COS-OGA induced defense against
275 nematodes is dependent on *OsPal4*.

276

4. Discussion

Due to the current ban on chemical nematicides, the pressure to present alternative nematode control strategies is increasing. Next to the use of resistant varieties, crop rotation, flooding or other agronomic prevention strategies, the activation of plant innate immunity against nematodes and other pathogens gains more and more attention (Oka et al., 1999; Cohen et al., 2016; Asif et al., 2017; Medeiros et al., 2017). Although 100% resistance is not achievable with products acting as plant defense elicitors, they are very useful as one of the prevention methods in a well-designed integrated pest management plan, and as such can replace one or more pesticide applications in a seasonal program of plant protection (Walters et al., 2013). Interestingly, the protection conferred by these elicitors is often not specific and can potentially provide broad-spectrum protection against diseases and pests (Sharathchandra et al., 2004). For example, BABA application provides protection against nematodes as well as many bacterial and fungal diseases (reviewed by Cohen et al., 2016). Similarly, chitosan-induced resistance has a.o. been shown to protect eggplants from *M. inognita* infection (Asif et al., 2017) as well as *Pinus patula* against *Fusarium circinatum* infection (Fitza et al., 2013).

In this paper, we demonstrate the activity of two such defense elicitor formulations, based on COS-OGA, as a foliar spray to control RKN infection in rice roots. Depending on the experiment and the rice cultivar, reductions in gall and female numbers ranging between 25 and 75% were observed in roots after one single foliar application of COS-OGA. The systemic control provided by FytoSave and FytoSol was comparable for both products and was similar to what has been observed in our previous research with BABA (Ji et al., 2015) , while thiamine gave less pronounced effects to control nematode infection in rice roots (Huang et al., 2016).

In order to elucidate the mode-of-action of COS-OGA systemic induced defense against RKN, hormone measurements were executed on roots and shoots of rice plants, 24 h after treatment. ABA-levels in shoots of treated plants were significantly reduced in comparison with untreated plants, while ABA root levels were unaffected. In previous research we found that foliar ABA application leads to increases in root ABA levels and enhanced susceptibility to RKN through a negative antagonistic interaction with jasmonate-based defense (Kyndt et al., 2017). In combination with the current data showing that FytoSave and FytoSol treatment do not affect root ABA levels, ABA seems unlikely to be responsible for COS-OGA systemic induced defense.

It has been demonstrated that FytoSave-induced defense is based on activation of the SA pathway in tomato leaves starting after the second COS-OGA spraying (Van Aubel et al., 2016). In tomato, leaf proteomic analysis of plants sprayed twice with COS-OGA showed accumulation of Pathogenesis-Related proteins (PR), especially subtilisin-like proteases, and qRT-PCR confirmed upregulation of PR-genes and SA-related genes (Van Aubel et al., 2016). Here, PR1b expression was not activated in the locally treated tissue (shoots), but showed activation in the roots. Enhanced activation of PR1 has previously been correlated with enhanced RKN-resistance in tomato (Molinari et al., 2014; de Medeiros et al., 2017). Although induction of this gene is generally correlated with SA, our observations do not show a clear role for SA in COS-OGA induced defense. The experiments with one single spraying on rice showed that shoot SA levels were significantly lower 24 h after COS-OGA treatment in rice, while root SA levels were unaffected and the transcripts of the SA biosynthesis gene *OsICS1* were not significantly induced or even slightly repressed in shoots or roots upon COS-OGA treatment. In addition, COS-OGA was still inducing systemic defense in the SA-deficient *NahG* line. Rice shoot tissue is well-known to contain very high basal levels of SA, which do not significantly rise upon pathogen inoculation, although

activation of SA-signaling can activate defense responses against for example *Magnaporthe oryzae* (Shimono et al., 2007). Hence, one could reason that while actual SA-levels are not important, the SA-signaling pathway could still play a role in COS-OGA systemic induced defense. However, contradicting this hypothesis, FytoSave and FytoSol application were still fully active in the *OsWRKY45* RNAi line. From these observations we conclude that the SA–dependent defense pathway is not the main driver of COS-OGA systemic induced defense in rice against RKN.

Gene expression analysis showed a clear activation of *OsPAL4* and *OsPAL6*-gene expression in root systems of COS-OGA treated plants, similar to the observations reported by Fitza et al. (2013) in chitosan-treated *Pinus patula*. PAL is the committed step into the phenylpropanoid pathway, that involves a complex series of branching biochemical pathways to provide plants with structural cell components (lignin, suberin and other cell wall-associated phenolics), pigments (flavonoids, anthocyanins), SA and toxins (coumarins and furanocoumarins) (Vogt, 2010). Our data show that *OsPAL4*-activation is essential for COS-OGA systemic induced defense, as the *OsPal4*-mutant was insensitive to COS-OGA treatments. PAL-activity measurements confirmed its enzymatic activation in the shoots, although gene expression of different *PAL*-paralogues was negatively affected in this tissue. PAL has been shown to be tightly metabolically regulated through negative feedback by cinnamic acid on *PAL* transcription and on enzyme activity (Blount et al., 2000). Based on our data, we propose that the COS-OGA induced PAL-activity lead to negative feedback control of *PAL*-gene expression in shoot tissue. Hormone data revealed a minor accumulation of JA in roots of COS-OGA treated plants, while shoots levels were significantly reduced 24h after FytoSave-treatment. The jasmonate pathway is known to play a central role in immunity against RKN in (Nahar et al., 2011; Gleason et al., 2016) and it is known that the phenylpropanoid pathway is positively regulated by JA (Pauwels et al., 2008; Taheri &

Tarighi, 2010). However, since only a small change in expression of JA-related genes and in JA accumulation was observed in the COS-OGA treated plants and seeing the fact that both COS-OGA formulations were still effective in the JA-deficient *hebiba* mutant, JA-biosynthesis seems not to be required for FytoSol and FytoSave systemic induced defense.

However, our data demonstrate that activation of *OsPAL4* is essential for COS-OGA systemic induced defense. Similar to these observations, *PAL* expression has been shown to correlate with thiamine-induced systemic defense against *M. graminicola* in rice (Huang et al., 2015) as well as chitosan-induced defence against *Fusarium* in *Pinus* (Fitza et al., 2013). *OsPAL4* was found to be upregulated upon infection in the *M. graminicola*-resistant rice cultivar Vandana, while no differences in expression were observed in the susceptible cultivar Pusa (Kumari et al., 2016). In addition, the phenylpropanoid pathway is at least partially responsible for resistance against the foliar nematode *Ditylenchus angustus* in the rice genotype 'Manikpukha' (Khanam et al., 2017). Despite these observations and the fact that the *OsPal4*-mutant is highly susceptible to rice blast (Tonnessen et al., 2015), this mutant was here found to be less susceptible towards RKN, which would indicate a role for this gene in rice susceptibility towards RKN. However, previous observations with the general PAL-inhibitor AOPP, showed that PAL inhibition does not significantly influence rice susceptibility towards RKN (Ji et al., 2015). Transcriptome analyses have shown that the phenylpropanoid pathway is generally suppressed in RKN-induced feeding sites in rice (Kyndt et al., 2012). This, together with the fact that PAL-family contains many paralogues and leads to a complex variety of metabolites, complicates interpretation of these data. Nevertheless, upon induced defense by COS-OGA, the RKN might not be able anymore to overcome the activated plant immune response.

While our data demonstrate that activation of *OsPAL4* is essential for COS-OGA systemic induced defense, it remains to be determined which metabolite produced in the shoot by the

phenylpropanoid pathway determines RKN resistance in the roots. The fact that COS-OGA activity against RKN is not dependent on SA biosynthesis and signaling is an indication that other products derived from the phenylpropaonid pathway could be responsible for the observed lower nematode susceptibility.

The phenylpropanoid pathway can contribute to the biosynthesis of many defense-related compounds, such as phenolics, lignins, stilbenes , phytoalexins and isoflavonoids (Vogt, 2010)). Recent findings show that the phenylpropanoid pathway is also involved in the induction of resistance in other pathogen-plant interactions, although no systemic effects have ever been investigated. For example, BABA-induced resistance against downy mildew (*Plasmopara viticola*) in grapevine was associated with the primed deposition of, among others, phenylpropanoid-derived phenolics in the treated tissue (Hamiduzzaman et al., 2005). Foliar silicon application to the rose (*Rosa hybrida*) cultivar Smart increased the expression of phenylpropanoid pathway genes and the concentration of antimicrobial phenolic acids and flavonoids (rutin and quercitrin), and this was correlated with increased plant protection against infection by rose powdery mildew in the leaves (*Podosphaera pannosa*) (Shetty et al., 2011). Concerning nematodes (Fujimoto et al., 2015) found that induced resistance against *M. incognita* in Arabidopsis by root sclareol treatment was correlated with higher transcript levels of *PAL1*, cinnamoyl 4-hydroxylase (*C4H*) and cinnamoyl-CoA reductase (*CCR2*). Similarly, root benzothiadiazole (BTH) application led to induced expression of phenylpropanoid biosynthesis genes, and this was correlated with significant changes in the monomer composition of lignin in RKN-induced galls in tomato roots (Veronico et al., 2018). Whether the flavonoid and/or lignin composition of rice roots is affected by COS-OGA treatment remains to be studied in follow-up research. Additionally, the observation that PAL-activity is mainly induced in the shoots of the treated plants, while phenylpropanoid

gene expression and plant defense against nematodes is observed in the root system raises the question which PAL4-dependent signal is transported from the shoot to the root system.

In conclusion, we have shown that foliar COS-OGA applications can effectively protect rice roots from RKN infection. We demonstrate for the first time that the effect of COS-OGA is systemic and its systemic mode-of-action is not based on the traditional SA or JA defense hormones, but on activation of the phenylpropanoid pathway.

5. Acknowledgements

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412 **Figure legends**

413 **Figure 1.** Effect of COS-OGA formulations FytoSol (Sol) and FytoSave (Save) at different
414 concentrations (0.1, 0.5, 0.25, 0.125% v/v) on rice susceptibility to the root-knot nematode
415 *M. graminicola*. (A) Average number of root galls per plant counted at 14 dpi, (B) average
416 number of females per plant counted at 14 dpi. The bars are the means ± standard error (SE)
417 of 8 individual plants per treatment. Different letters indicate significant differences (Duncan;
418 $\alpha = 0.05$). The whole experiment was independently repeated with similar results**.**
419
420 **Figure 2.** Hormone levels in COS-OGA (0.5% v/v) treated rice plants in comparison with
421 mock-treated control plants, measured 24 h after foliar application. (A) Abscisic acid (ABA),
422 indole-3-acetic acid (IAA), and jasmonic acid (JA) content in the shoots of treated and
423 control plants. (B) Salicylic acid (SA) content in the shoots of treated and control plants. (C)
424 ABA, IAA, JA and SA content in the roots of treated and control plants. Values presented are
425 means ± SE of 5 biological replicates (each a pool of 3 individual plants) per treatment.
426 Asterisks indicate statistically significant differences (t-test; $\alpha = 0.05$).
427
428 **Figure 3.** Gene expression analysis with qRT-PCR on shoots (A) and roots (B) of COS-OGA
429 treated rice plants. The relative expression levels of JA biosynthesis *OsAOS2*, SA-
430 biosynthesis gene *OsICS1*, PAL-encoding genes *OsPAL2*, *OsPAL4*, *OsPAL6* and the general
431 plant defense gene *PR1b*, were analyzed using qRT-PCR at 24h after treatment. Values
432 presented are means ± SE of 3 biological replicates (each a pool of 4 individual plants) per
433 treatment. Gene expression levels were normalized using two internal reference genes,
434 *OsEXP and OsEif5C*. Data are shown as relative transcript levels in comparison with the
435 control plants (expression level set at 1). Asterisks indicate significant differential expression
436 (REST-analysis; $\alpha = 0.05$).

Figure 4. Role of SA and JA in the COS-OGA systemic induced defense against RKN in rice. (A) Activity of COS-OGA against nematodes in the SA-deficient *NahG* line and *OsWRKY45* RNAi line and their corresponding wild-type ('Nipponbare'). Plants were treated with 0.5% FytoSave or FytoSol at 24 h before inoculation. Number of galls per plant were counted at 14 dpi. (B) Activity of COS-OGA against nematodes in the JA-deficient *hebiba* mutant and its corresponding wild-type ('Nihonmasari'). Plants were treated with FytoSave or FytoSol at 24 h before inoculation. Number of galls per plant were counted at 14 dpi. The bars are the means ± SE of 8 individual plants per treatment. Different letters indicate statistically significant differences (Duncan; $\alpha = 0.05$). The whole experiment was independently repeated with similar results.

Figure 5. Role of the phenylpropanoid pathway in the COS-OGA systemic induced defense against RKN in rice. (A) PAL enzymatic activity in the shoots of treated and control plants. (B) PAL enzymatic activity in the roots of treated and control plants. Values presented are means ± SE of 4 biological replicates (each a pool of 4 individual plants) per treatment. Asterisks indicate statistically significant differences from control plants ($\alpha = 0.05$). (C) Activity of COS-OGA against nematodes in the *OsPAL4*-mutant line and its corresponding wild-type ('IR64'). Plants were treated with FytoSave or FytoSol at 24h before inoculation. Number of galls per plant were counted at 14 dpi. The bars are the means ± SE of 8 individual plants per treatment. Different letters indicate statistically significant differences (Duncan; $\alpha = 0.05$). The whole experiment was independently repeated with similar results.

462

463 **Supplementary information**

464 **SI.** Effect of COS-OGA formulations FytoSol (Sol) and FytoSave (Sav) at different
465 concentrations (0.1, 0.5, 0.25, 0.125% v/v) on rice cv. 'Nipponbare' shoot (A) and root (B)
466 fresh weight under root-knot nematode *M. graminicola* infected conditions, measured at 14
467 dpi. The bars are the means ± SE of 8 individual plants per treatment. No significant
468 differences were observed (Duncan; $\alpha = 0.05$).

469 **SII**. Effect of COS-OGA formulations FytoSol (Sol) and FytoSave (Sav) at 0.5% v/v) on rice
470 cv. 'IR64' root length under root-knot nematode *M. graminicola* infected conditions,
471 measured at 14 dpi. The bars are the means ± SE of 8 individual plants per treatment.
472 Different letters indicate significant differences (Duncan; $\alpha = 0.05$).

References

ASIF, M., AHMAD, F., TARIQ, M., KHAN, A., ANSARI, T., KHAN, F. & SIDDIQUI, A. M. 2017. Potential of chitosan alone and in combination with agricultural wastes against the root-knot nematode, *Meloidogyne incognita* infesting eggplant. Journal of Plant Protection Research, 57(3), 288–295.

BLOUNT, J. W., KORTH, K. L., MASOUD, S. A., RASMUSSEN, S., LAMB, C. & DIXON, R. A. 2000. Altering expression of cinnamic acid 4-hydroxylase in transgenic plants provides evidence for a feedback loop at the entry point into the phenylpropanoid pathway. Plant Physiology, 122, 107-116.

CAMACHO-CRISTOBAL, J. J., ANZELLOTTI, D. & GONZALEZ-FONTES, A. 2002. Changes in phenolic metabolism of tobacco plants during short-term boron deficiency. Plant Physiology and Biochemistry, 40, 997-1002.

CLINCKEMAILLIE, A., DECROES, A., VAN AUBEL, G., DOS SANTOS, S. C., RENARD, M. E., VAN CUTSEM, P. & LEGREVE, A. 2017. The novel elicitor COS-OGA enhances potato resistance to late blight. Plant Pathology, 66, 818-825.

COHEN, Y., VAKNIN, M. & MAUCH-MANI, B. 2016. BABA-induced resistance: milestones along a 55-year journey. Phytoparasitica, 44 (4), 513-538.

CONRATH, U., BECKERS, G. J. M., LANGENBACH, C. J. G. & JASKIEWICZ, M. R. 2015. Priming for Enhanced Defense. Annual Review of Phytopathology, Vol 53, 53, 97-119.

FAO, 2016. FAOSTAT. Food and Agriculture Organization of the United Nations, Rome, Italy http://faostat.fao.org/default.aspx.

FANELLI, E., COTRONEO, A., CARISIO, L., TROCCOLI, A., GROSSO, S., BOERO, C., CAPRIGLIA, F. & DE LUCA, F. 2017. Detection and molecular characterization of the rice root-knot nematode *Meloidogyne graminicola* in Italy. European Journal of Plant Pathology, 149(2), 467-476.

FITZA, K.N.E., PAYN, K.G., STEENKAMP, E.T., MYBURG, A.A. & NAIDOO, S. 2013. Chitosan application improves resistance to *Fusarium circinatum* in *Pinus patula*. South African Journal of Botany, 85, 70–78.

FUJIMOTO, T., MIZUKUBO, T., ABE, H. & SEO, S. 2015. Sclareol induces plant resistance to root-knot nematode partially through ethylene-dependent enhancement of lignin accumulation. Molecular Plant-Microbe Interactions, 28, 398-407.

GLEASON, C., LEELARASAMEE, N., MELDAU, D. & FEUSSNER, I. 2016. OPDA has key role in regulating plant susceptibility to the root-knot nematode *Meloidogyne hapla* in Arabidopsis. Frontiers in Plant Science, 7.

HAECK, A., VAN LANGENHOVE, H., HARINCK, L., KYNDT, T., GHEYSEN, G., HOFTE, M. & DEMEESTERE, K. 2018. Trace analysis of multi-class phytohormones in *Oryza sativa* using different scan modes in high-resolution Orbitrap mass spectrometry: method validation, concentration levels, and screening in multiple accessions. Analytical and Bioanalytical Chemistry, 410, 4527-4539.

HAMIDUZZAMAN, M. M., JAKAB, G., BARNAVON, L., NEUHAUS, J. M. & MAUCH-MANI, B. 2005. beta-Aminobutyric acid-induced resistance against downy mildew in grapevine acts through the potentiation of callose formation and jasmonic acid signaling. Molecular Plant-Microbe Interactions, 18, 819-829.

HUANG, W. K., JI, H. L., GHEYSEN, G. & KYNDT, T. 2016. Thiamine-induced priming against root-knot nematode infection in rice involves lignification and hydrogen peroxide generation. Molecular Plant Pathology, 17, 614-624.

JI, H. L., KYNDT, T., HE, W., VANHOLME, B. & GHEYSEN, G. 2015. Beta-aminobutyric acid-induced resistance against root-knot nematodes in rice is based on increased basal defense. Molecular Plant-Microbe Interactions, 28, 519-533.

JONES, J. D. G. & DANGL, J. L. 2006. The plant immune system. Nature, 444, 323-329.

KHANAM, S., BAUTERS, L., SINGH, R.R., VERBEEK, R., HAECK, A., SULTAN, S.M., DEMEESTERE, K., KYNDT, T. & GHEYSEN, G., 2018. Mechanisms of resistance in the rice cultivar Manikpukha to the rice stem nematode *Ditylenchus angustus*. Molecular Plant Pathology, 19(6), pp.1391-1402.

KUMARI, C., DUTTA, T. K., BANAKAR, P. & RAO, U. 2016. Comparing the defense-related gene expression changes upon root-knot nematode attack in susceptible versus resistant cultivars of rice. Scientific Reports, 6.

KYNDT, T., DENIL, S., HAEGEMAN, A., TROOSKENS, G., BAUTERS, L., VAN CRIEKINGE, W., DE MEYER, T. & GHEYSEN, G. 2012. Transcriptional reprogramming by root knot and migratory nematode infection in rice. New Phytologist, 196, 887-900.

KYNDT, T., NAHAR, K., HAECK, A., VERBEEK, R., DEMEESTERE, K. & GHEYSEN, G. 2017. Interplay between carotenoids, abscisic acid and jasmonate guides the compatible rice-*Meloidogyne graminicola* interaction. Frontiers in Plant Science, 8.

KYNDT, T., VIEIRA, P., GHEYSEN, G. & DE ALMEIDA-ENGLER, J. 2013. Nematode feeding sites: unique organs in plant roots. Planta, 238, 807-818.

LUC, M., SIKORA, R. A. & BRIDGE, J. 2005. Plant parasitic nematodes in subtropical and tropical agriculture, Ed 2. CAB International, Wallingford, UK

MANTELIN, S., BELLAFIORE, S. & KYNDT, T. 2017. *Meloidogyne graminicola*: a major threat to rice agriculture. Molecular Plant Pathology, 18, 3-15.

MEDEIROS, H. A. FILHO, J.V.A., FREITAS, L.G., CASTILLO, P., RUBIO, M.B., HERMOSA, R. & MONTE, E. 2017. Tomato progeny inherit resistance to the nematode *Meloidogyne javanica* linked to plant growth induced by the biocontrol fungus *Trichoderma atroviride*. Scientific Reports 7, 40216.

MOLINARI, S., FANELLI, E. & LEONETTI, P. 2014. Expression of tomato salicylic acid (SA)□responsive pathogenesis□related genes in Mi□1□mediated and SA□induced resistance to root□knot nematodes. Molecular Plant Pathology 15, 255–264.

NAHAR, K., KYNDT, T., DE VLEESSCHAUWER, D., HOFTE, M. & GHEYSEN, G. 2011. The jasmonate pathway is a key player in systemically induced defense against root knot nematodes in rice. Plant Physiology, 157, 305-316.

OKA, Y., COHEN, Y., & SPIEGEL, Y. 1999. Local and systemic induced resistance to the root-knot nematode in tomato by DL-β-amino-n-butyric acid. Phytopathology 89, 1138-1143.

PAUWELS, L., MORREEL, K., DE WITTE, E., LAMMERTYN, F., VAN MONTAGU, M., BOERJAN, W., INZE, D., & GOOSSENS, A. 2008. Mapping methyl jasmonate-mediated transcriptional reprogramming of metabolism and cell cycle progression in cultured Arabidopsis cells. Proceedings of the National Academy of Sciences of the United States of America, 105, 1380-1385.

PIETERSE, C. M. J., ZAMIOUDIS, C., BERENDSEN, R. L., WELLER, D. M., VAN WEES, S. C. M. & BAKKER, P. 2014. Induced systemic resistance by beneficial microbes. Annual Review of Phytopathology, Vol 52, 52, 347-375.

SHARATHCHANDRA, R. G., RAJ, S. N., SHETTY, N. P., AMRUTHESH, K. N. & SHETTY, H. S. 2004. A Chitosan formulation Elexa(TM) induces downy mildew disease resistance and growth promotion in pearl millet. Crop Protection, 23, 881-888.

SHETTY, R., FRETTE, X., JENSEN, B., SHETTY, N. P., JENSEN, J. D., JORGENSEN, H. J. L., NEWMAN, M. A. & CHRISTENSEN, L. P. 2011. Silicon-induced changes in antifungal phenolic acids, flavonoids, and key Phenylpropanoid pathway genes during the

interaction between miniature roses and the biotrophic pathogen *Podosphaera pannosa*. Plant Physiology, 157, 2194-2205.

SHIMONO, M., SUGANO, S., NAKAYAMA, A., JIANG, C.J., ONO, K., TOKI, S. AND TAKATSUJI, H., 2007. Rice WRKY45 plays a crucial role in benzothiadiazole-inducible blast resistance. The Plant Cell, 19(6), pp.2064-2076.

TAHERI, P. & TARIGHI, S. 2010. Riboflavin induces resistance in rice against *Rhizoctonia solani* via jasmonate-mediated priming of phenylpropanoid pathway. Journal of Plant Physiology, 167, 201-208.

TONNESSEN, B. W., MANOSALVA, P., LANG, J. M., BARAOIDAN, M., BORDEOS, A., MAULEON, R., OARD, J., HULBERT, S., LEUNG, H. & LEACH, J. E. 2015. Rice phenylalanine ammonia-lyase gene OsPAL4 is associated with broad spectrum disease resistance. Plant Molecular Biology, 87, 273-286.

VAN AUBEL, G., BUONATESTA, R. & VAN CUTSEM, P. 2014. COS-OGA: A novel oligosaccharidic elicitor that protects grapes and cucumbers against powdery mildew. Crop Protection, 65, 129-137.

VAN AUBEL, G., CAMBIER, P., DIEU, M. & VAN CUTSEM, P. 2016. Plant immunity induced by COS-OGA elicitor is a cumulative process that involves salicylic acid. Plant Science, 247, 60-70.

643 VAN AUBEL, G. , SERDERIDIS, S. , IVENS, J. , CLINCKEMAILLIE, A. , LEGRÈVE, A.,
644 HAUSE, B. & VAN CUTSEM, P. 2018, Oligosaccharides successfully thwart hijacking of
645 the salicylic acid pathway by Phytophthora infestans in potato leaves. Plant Pathol, 67: 1901-
646 1911.
647
648 VERONICO, P., PACIOLLA, C., POMAR, F., DE LEONARDIS, S., GARCÍA-ULLOA, A.,
649 & MELILLO, M. T. (2018). Changes in lignin biosynthesis and monomer composition in
650 response to benzothiadiazole and root-knot nematode Meloidogyne incognita infection in
651 tomato. Journal of plant physiology, 230, 40-50.
652
653 VOGT, T. 2010. Phenylpropanoid Biosynthesis. Molecular Plant, 3, 2-20.
654
655 WALTERS, D. R., RATSEP, J. & HAVIS, N. D. 2013. Controlling crop diseases using
656 induced resistance: challenges for the future. Journal of Experimental Botany, 64, 1263-1280.
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Figure 1

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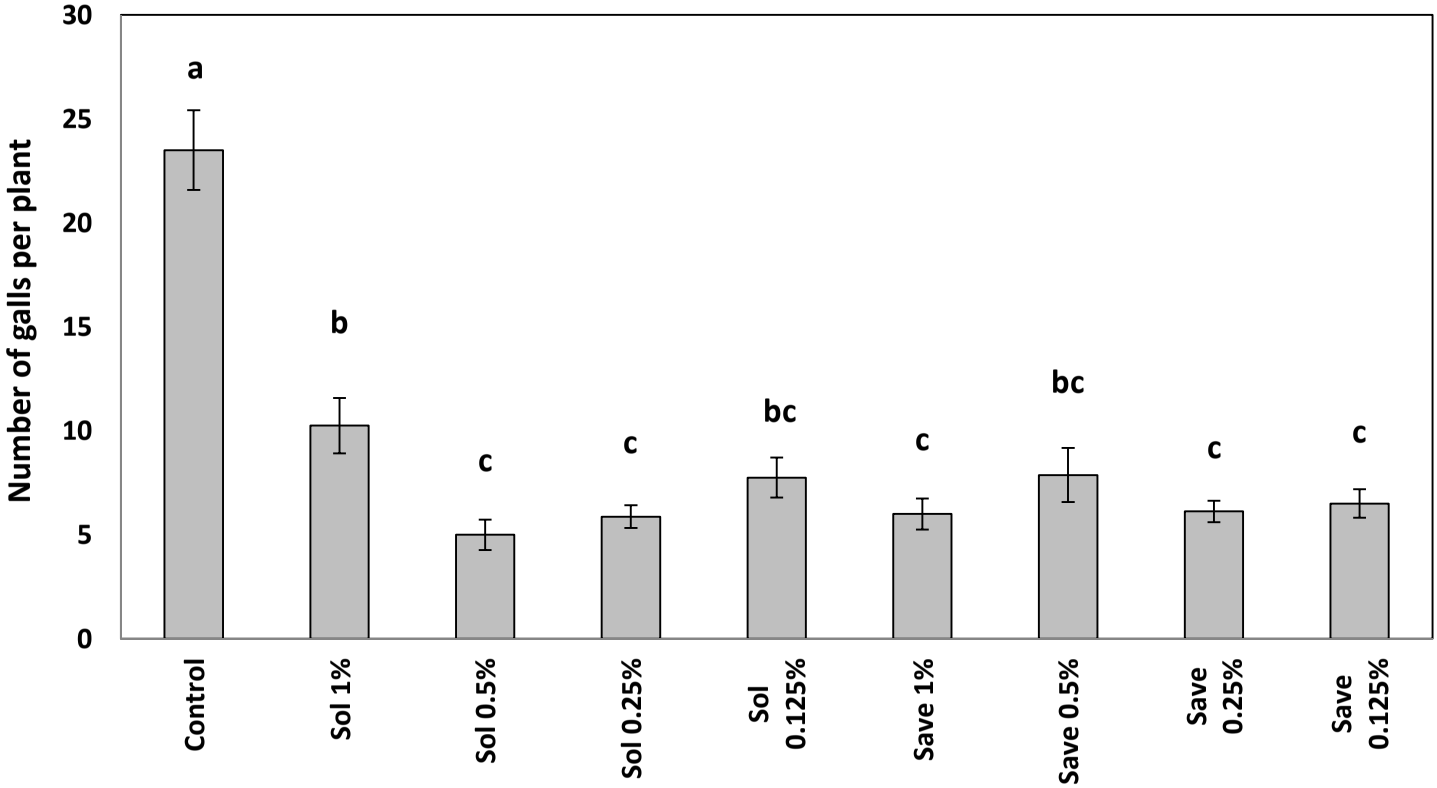
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15
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c
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c
bc
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Sol 0.5%
Sol 0.25%
Sol 0.125%
Save 1%
Save 0.5%
Save 0.25%
Save 0.125%

B

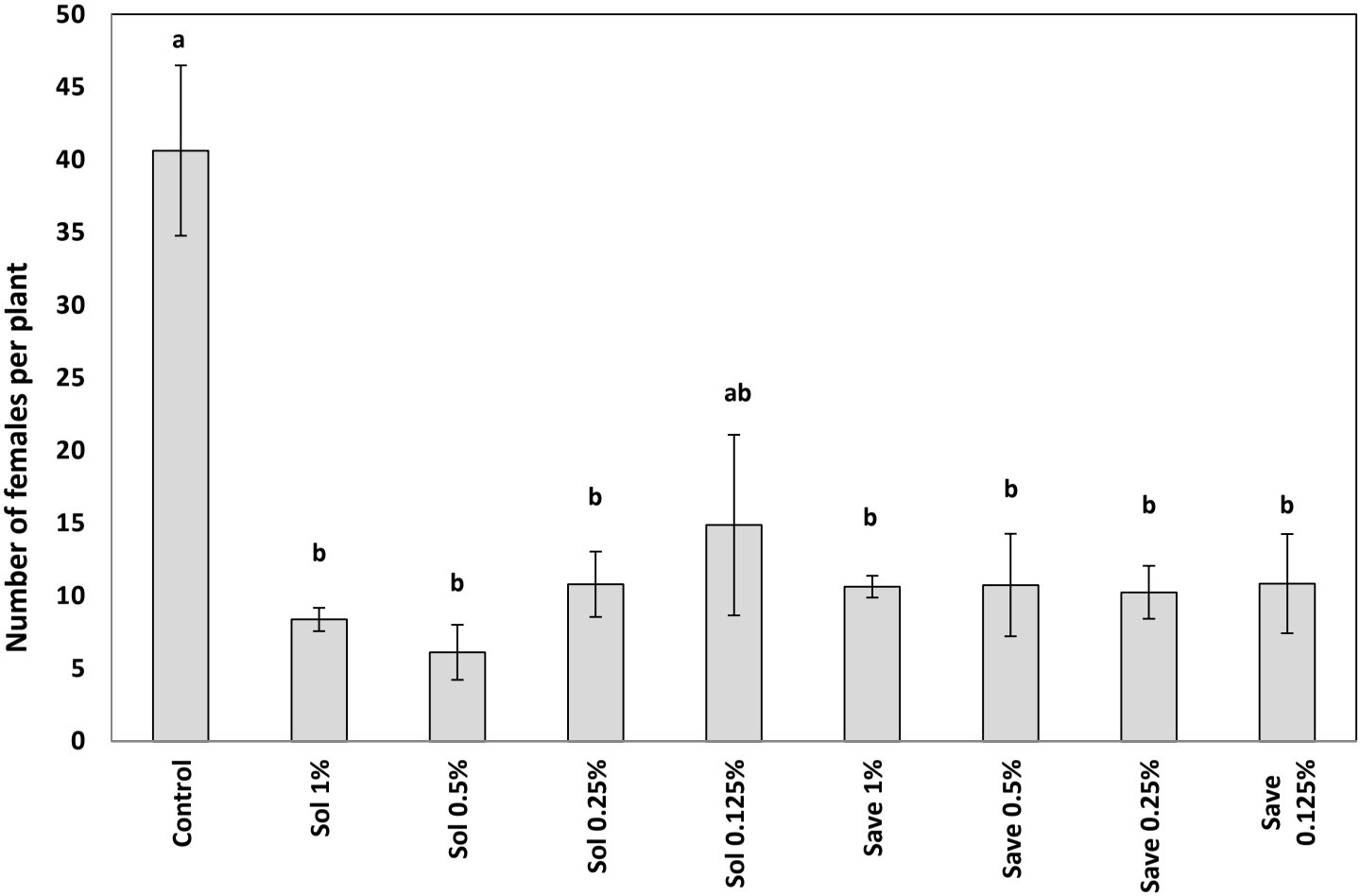
Number of females per plant
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Figure 2

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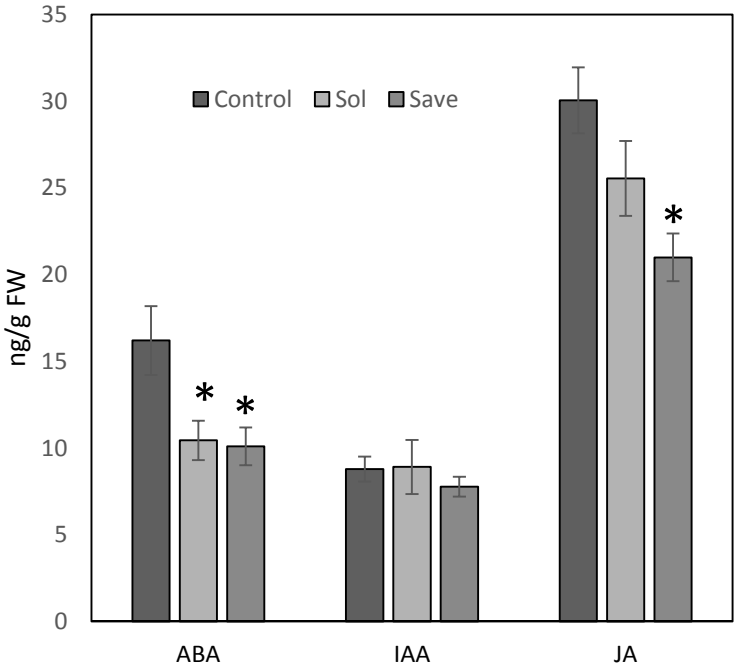
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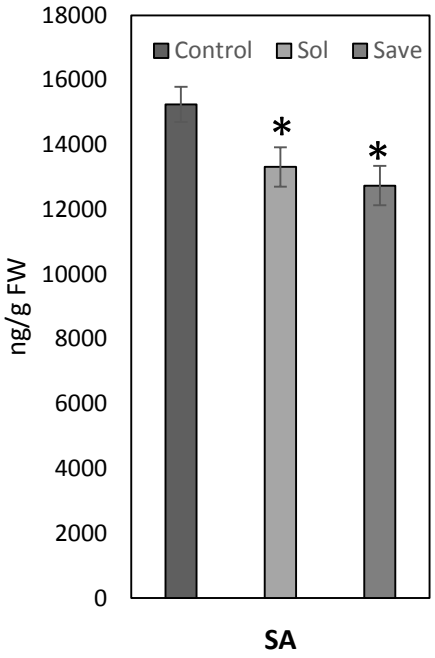
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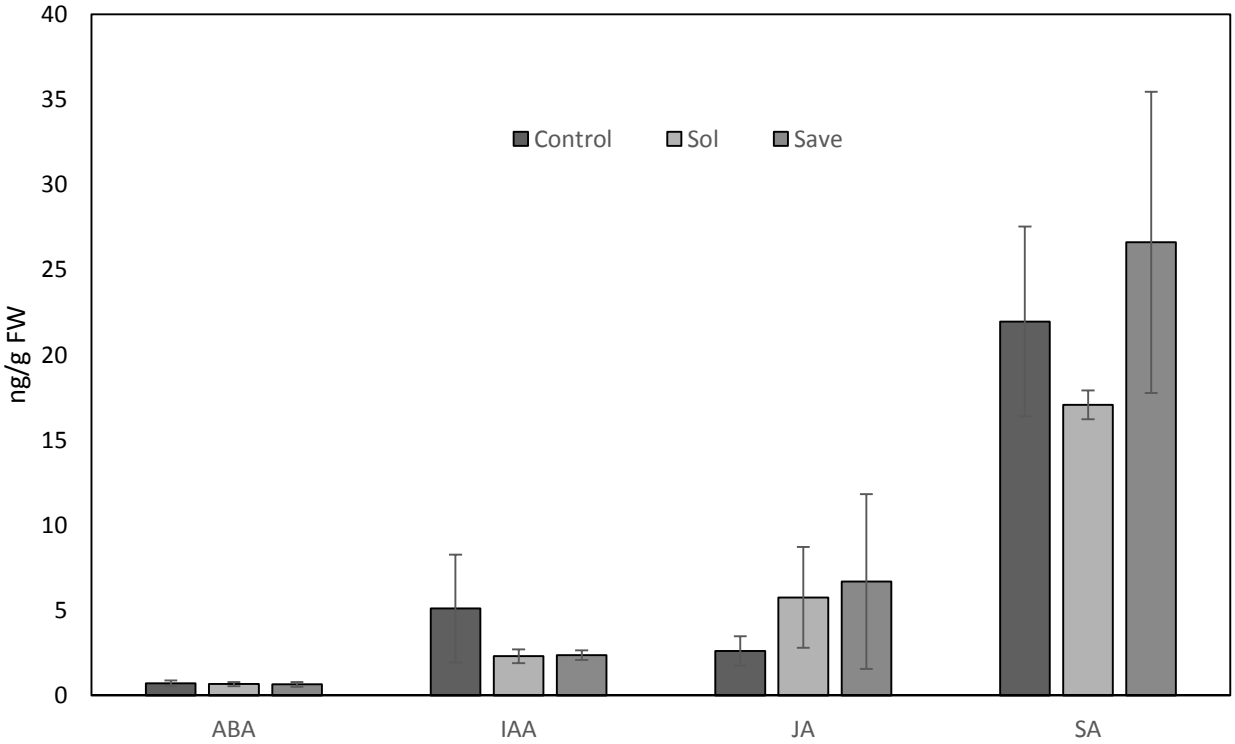
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Figure 3

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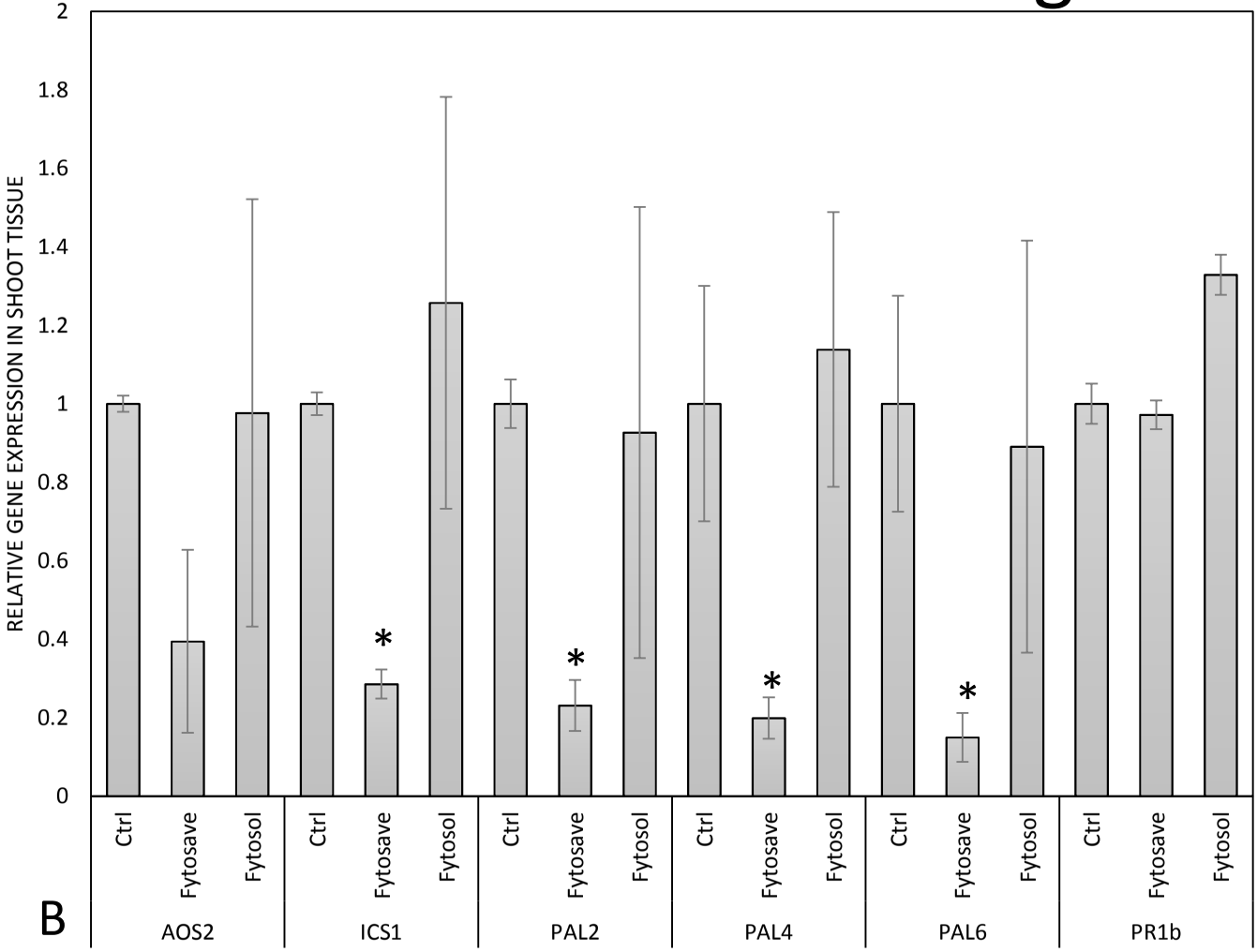
RELATIVE GENE EXPRESSION IN SHOOT TISSUE
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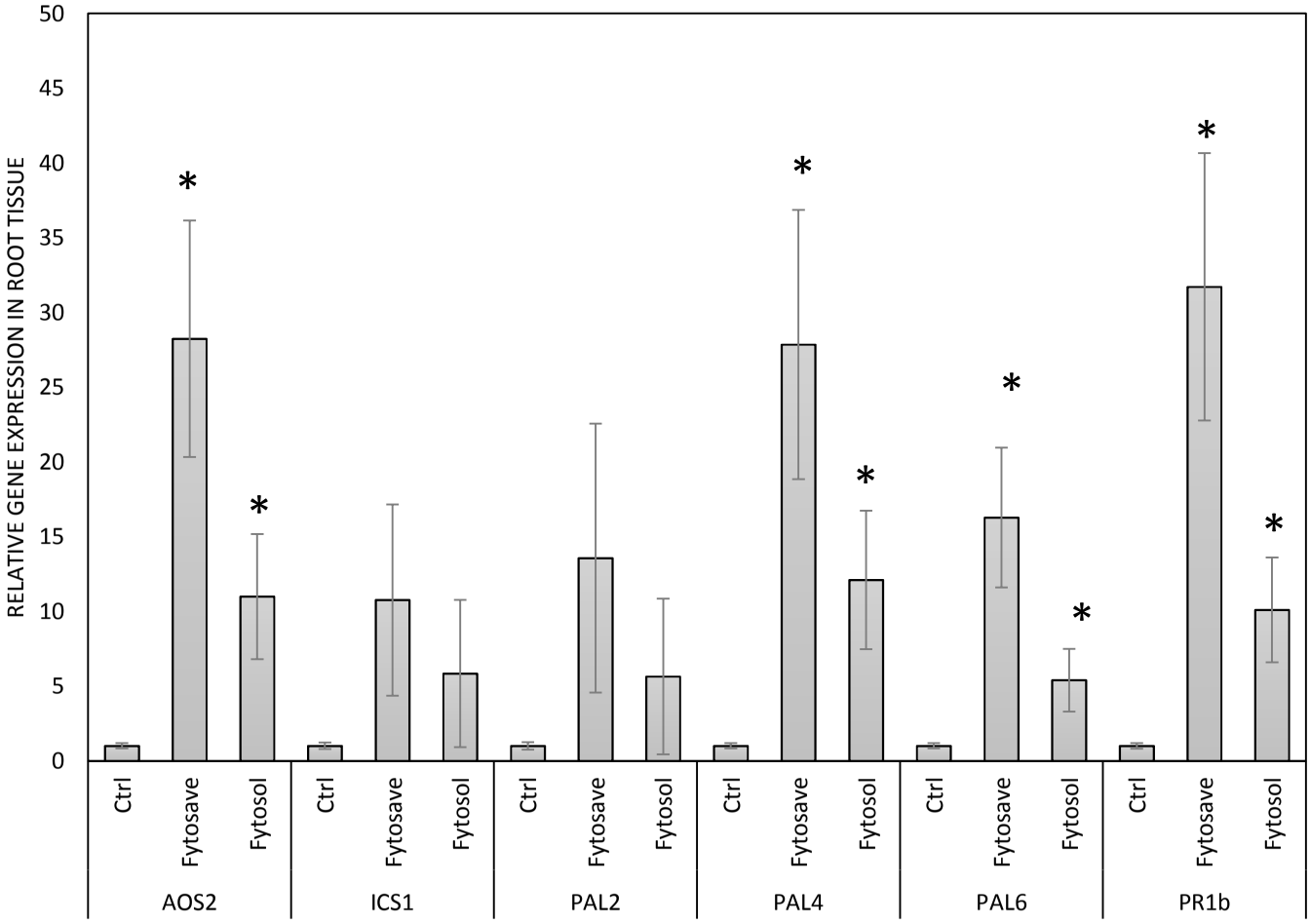
ICS1
PAL2
PAL4
PAL6
PR1b

B


RELATIVE GENE EXPRESSION IN ROOT TISSUE
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PR1b

Figure 4

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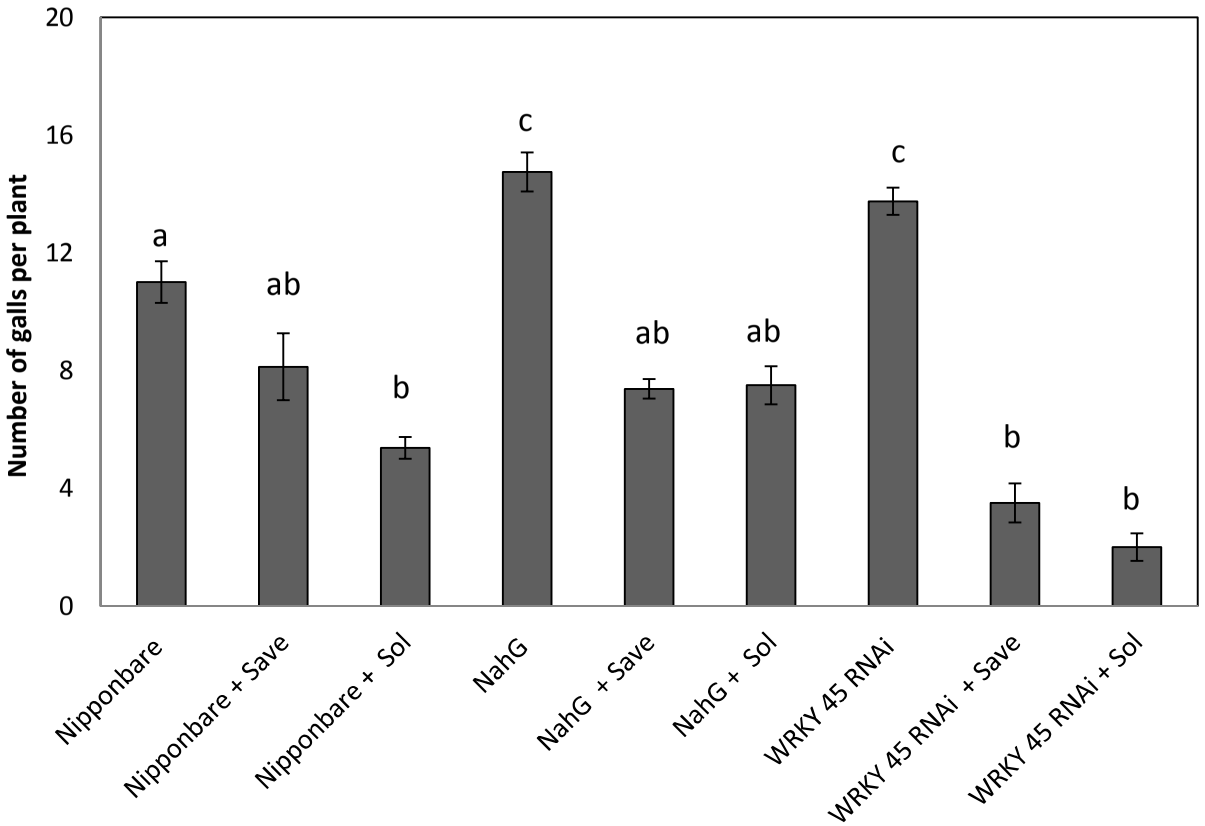
Number of galls per plant
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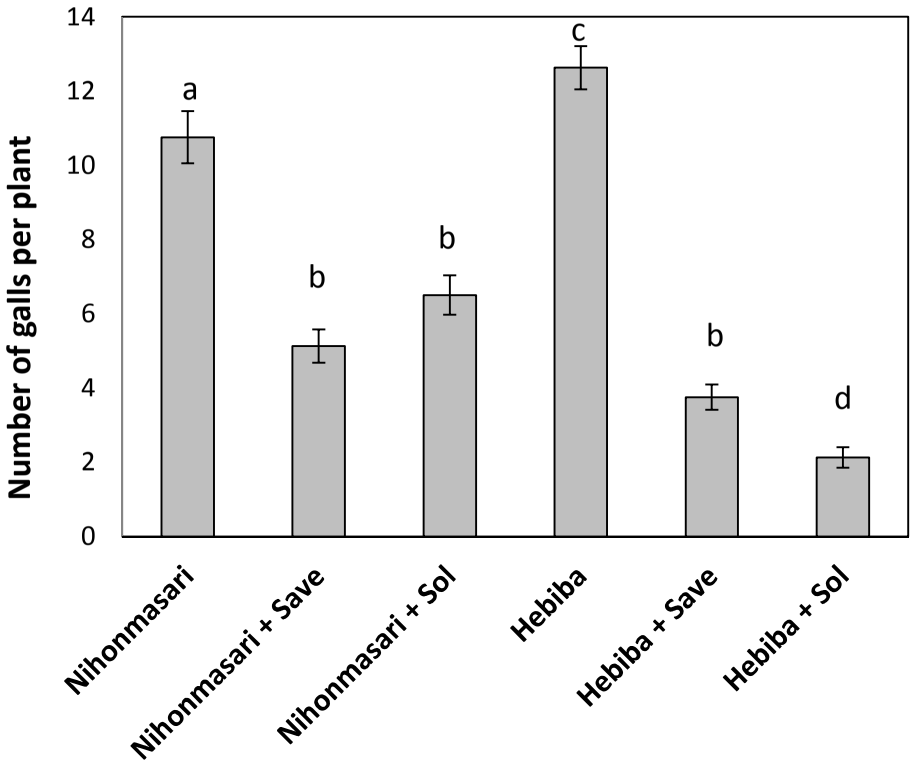
WRKY 45 RNAi + Sol

B


Number of galls per plant
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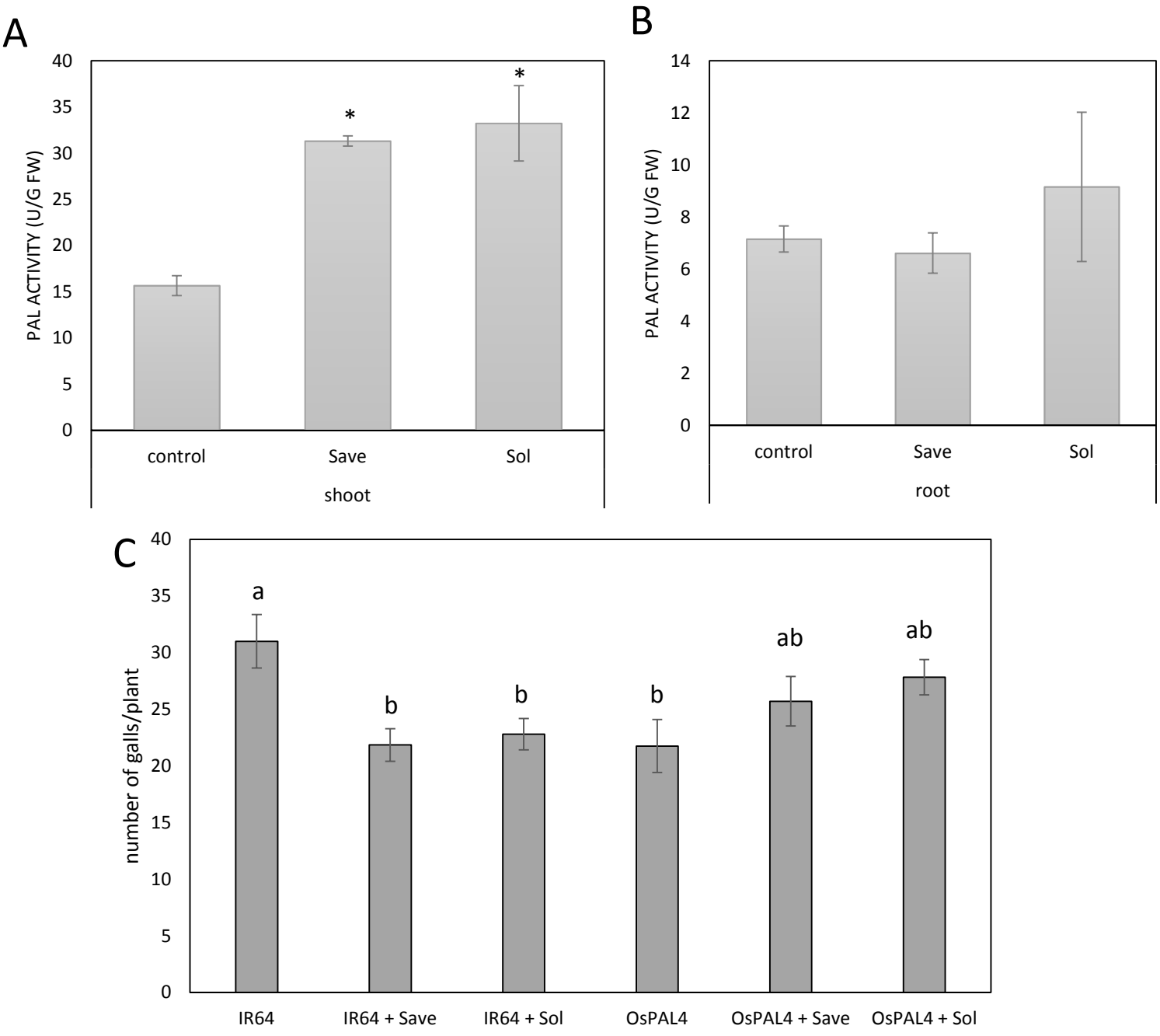
Nihonmasari
Nihonmasari + Save
Nihonmasari + Sol
Hebiba
Hebiba + Save
Hebiba + Sol

Figure 5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Save
Sol
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PAL ACTIVITY (U/G FW)
14
12
10
8
6
4
2
0
control
Save
Sol
root
C
number of galls/plant
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35
30
25
20
15
10
5
0
a
b
b
b
ab
ab
IR64
IR64 + Save
IR64 + Sol
OsPAL4
OsPAL4 + Save
OsPAL4 + Sol

Highlights

- Foliar application of two formulations of chitosan oligomers and pectin□derived oligogalacturonides reduces nematode infection by more than 30% in rice roots, showing for the first time a systemic effect of these defence elicitors.
- Systemic defence activation is not correlated with defence hormone accumulation in the rice shoots and roots.
- The systemic defence against root-knot nematodes is dependent on stimulation of the phenylpropanoid pathway.

B. Chinnasri did the infection experiments on wild-type and mutant plants. L. De Smet executed the direct nematicidal assays. R.R. Singh performed the PAL-measurements and the experiments on the PAL4-mutant and wrote the manuscript. A. Haeck and K. Demeestere executed the hormone measurements. P. Van Cutsem and G. Van Aubel formulated the defence elicitors. G. Gheysen and T. Kyndt designed and supervised the experimental set-up and provided extensive corrections on the draft manuscript. All authors have read and approved the manuscript before submission.