



RESEARCH PAPER

Prospection and identification of nematotoxic compounds from *Canavalia ensiformis* seeds effective in the control of the root knot nematode *Meloidogyne incognita*



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Abstract *Meloidogyne incognita* is responsible for significant crop losses worldwide. The main strategy to control this phytopathogen is still based on synthetic nematicides that are harmful to human health and the environment. In this context, aqueous seed extracts of antagonistic plants were screened for molecules effective toward the infective stage (J₂) of *M. incognita*. The aqueous crude extract of *Canavalia ensiformis* (ACECe) showed the highest nematocidal activity (87 ± 3% mortality). ACECe dialysis fractionation allowed the collection of an external dialysate (EDCe) containing molecules smaller than 3.5 kDa effective against J₂ (96 ± 3.0% mortality); innocuous toward non targeted organisms as saprophytic nematodes, fungi, bacterium and insects larvae; active against J₂ (96 ± 2% mortality) after heating (50 °C); no cytotoxic for bovine red blood cells; reduction of *M. incognita* eggs masses by 82.5% in tomato plants at green house conditions. Fractionation of the EDCe by reversed-phase high-performance liquid chromatography (RP-HPLC) separated five nematotoxic fractions. Analyses of those fractions based

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on gas chromatography–mass spectrometry (GC–MS), liquid chromatography–mass spectrometry (LCMS) and nuclear magnetic resonance (NMR) identified nine specific metabolites, follow-up testing of the individual authentic standards of each metabolite as the compounds: D-glucose, L-canavanine, xanthotoxin, *cis*-aconitic acid, *trans*-aconitic acid, malic acid, citric acid, palmitic acid and S-carboxymethylcysteine; all them confirmed to possess nematotoxic properties. However, some of those metabolites were not described previously demonstrating biological action against *M. incognita*.

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Introduction

Phytopathogenic nematodes represent one of the major challenges faced by modern agriculture in optimizing yield/productivity. The potential host range of these phytopathogens encompasses more than 3000 plant species, including economically important crops (Abad, Favery, Rosso, & Castagnone-Sereno, 2003; Jatala & Bridge, 1990). From this perspective, the endoparasite root knot nematode *Meloidogyne incognita* has attracted significant attention. The parasitic cycle in roots attacked by *M. incognita* is characterized by the presence of galls containing giant cells (Williamson & Gleason, 2003). Moreover, the injury caused by *M. incognita* during the penetration process on roots facilitates the invasion of other deleterious microorganisms, such as bacteria and fungi (Potter, Olthof, Evans, Trudgill, & Webster, 1993; Williamson & Gleason, 2003). Hence, *M. incognita* is responsible for between 8 and 25% losses of yield for agricultural crops, representing an annual worldwide economic impact of millions of dollars (US) (McCarter, 2009; Reynolds et al., 2011; Sasser & Freckman, 1987).

Several strategies have been employed to control *M. incognita* induced crop damage, including biological control, crop rotation, chemical nematicides, the use of resistant cultivars, antagonistic plants, and integrated pest management. In this context, the application of synthetic nematicides has been the first choice for many years to control this phytoparasite (FAO, 2016; Ntalli & Caboni, 2012). According to literature, synthetic nematicides may promote human health disorders, the destruction of natural pest enemies, the transformation of formerly innocuous species into pests, harm to other non-target species, persistence in food chain and environmental pollution (Berny, 2007; Elbadri, Lee, Park, Yu, & Choo, 2008; Ntalli & Caboni, 2012; Rockström et al., 2016). As a result, the majority of conventional synthetic nematicides were banned or restricted in use, thereby narrowing the availability of this alternative (EC, 2013; EPA, 2009). Hence, an efficient and sustainable approach to control *M. incognita* is straightaway required.

Plant natural products display some biological activity that could be associated with protection against a wide range of pests and pathogens, including root knot nematodes (Caboni et al., 2014; Naz et al., 2016; Prakash et al., 2014; Seiber, Coats, Duke, & Gross, 2014). It is estimated that there are approximately 500,000 plant species containing unknown molecules, including metabolites, with high potential use as biocides (Schultes, 1978). Indeed, more than 10,000 natural plant metabolites have been

identified, although this still represents less than 10% of the estimated total (Oksman-Caldentey & Inzé, 2004; Wink, 1988). For instance, the plant nematotoxic (nematicidal and/or nematostatic) effects based on compounds, like isothiocyanates, thiophenics, glucosides, alkaloids, phenolics, tannins and others, have been identified and reviewed (Jang et al., 2014; Ntalli & Caboni, 2012).

The nematode-antagonistic plants have received substantial attention due to their remarkable capacity to either paralyze (nematostatic compounds) or to kill (nematicide compounds) nematodes inside plant tissue and in the surrounding soil, thus reducing population density (Sano, 2005). The well-documented nematode antagonistic plants comprise marigolds (*Tagetes* spp.), rattlepod (*Crotalaria spectabilis*), chrysanthemums (*Chrysanthemum* spp.), castor bean (*Ricinus communis*), margosa (*Azadiracta indica*), velvet bean (*Mucuna deeringiana*), Jack-bean (*Canavalia ensiformis*) and Abruzzi rye (*Secale cereale*) (Duke, 1990; Ferraz & Freitas, 2000; Ferraz & Freitas, 2004). Extracts obtained from different parts of these plants species, using a wide range of solvent polarities, were previously evaluated for nematotoxic activity *in vitro* as well under greenhouse conditions (Ferraz & Freitas, 2004). However, plant seeds have received relatively limited attention despite their tremendous potential as a source of nematicide and nematostatic compounds. As an example, studies using *C. ensiformis* seed powder as a soil additive lead to a dramatically reduced number of eggs of *M. incognita* and *Meloidogyne javanica* (Lopes, Ferraz, Dhingra, Ferreira, & Freitas, 2009; Silva, Souza, & Cutrim, 2002). Due to this previous report, the present work have been used the aqueous extract from *C. ensiformis* seed powder aiming to identify the potential compounds exhibiting nematotoxic activity toward second stage juvenile (J2) of *M. incognita*.

The investigation of plant metabolites is difficult due to their physicochemical diversity, disparity in abundance and stability, which require a range of different technologies and approaches for analysis. Methods of metabolites profiling have been used for decades. However, technical innovations and substantial improvements to these techniques are now enabling profiling experiments to be conducted in a high throughput manner (Kim, Choi, & Verpoorte, 2010; Roessner & Bowne, 2009; Schripsema, 2010). These analyses are typically based on gas chromatography–mass spectrometry (GC–MS) (Fiehn, Kopka, Trethewey, & Willmitzer, 2000; Kopka et al., 2005; Roessner et al., 2001), liquid chromatography–mass spectrometry (LC–MS) (Schliemann, Ammer, & Strack, 2008), and the non-destructive

spectroscopic technique of nuclear magnetic resonance (NMR) (Krishnan, Kruger, & Ratcliffe, 2005; Ward, Baker, & Beale, 2007). Metabolite profiling analysis integrating these technologies and applied to plant extracts is a reliable technique, providing large pools of information, including chemical composition and a metabolite fingerprint (Trethewey, 2004).

Hence, a screening program to identify natural nematotoxic compounds from plant sources is of major interest as they represent both an alternative to synthetic nematocides and allow further research of biosynthetic pathways and potentially metabolic engineering approaches. Furthermore, natural nematotoxic compounds have a prominent role in the development of new commercial nematocides, not only for agricultural crop productivity but also for the safety of the environment and public health.

Here we propose an approach for identifying nematotoxic candidates in a high throughput manner. Our approach is based on a bioassay-guided HPLC purification, coupled with GC-MS, LC-MS and NMR analysis to identify active compounds. We have supplemented this strategy with a broad literature search to identify bioactivities of known compounds extracted from the seeds of some leguminous nematode antagonistic plants.

Material and methods

Extraction of plant seed metabolites

Mature seeds of *C. ensiformis* (L.) DC (Fabaceae), *Crotalaria juncea* (L.) (Fabacea), *Crotalaria paulina* (L.) (Fabaceae), *C. spectabilis*(L.) (Fabaceae), *Tagetes minuta* (L.) (Asteraceae), and *Mucuna pruriens* (L.) (Fabaceae) were kindly provided by Plant Germoplasm Bank from Embrapa, Brasília-DF, Brazil. Seeds were ground with a mortar and pestle using liquid nitrogen and subsequently pulverized applying 3 pulses of 30s in a Cyclone Sample Mill (UDY Corporation, Fort Collins, CO). Ten grams of each powdered seed material was suspended in 60 mL of distilled water (dH₂O) and gently agitated for 24 h at 4 °C. The resulting solutions were individually filtered through eight layers of cheesecloth, and the aqueous crude seed extracts were centrifuged, at 12,000 × g for 45 min at 4 °C. After this procedure it was observed a ring (lipids) in the extract surface that was carefully removed using a micropipette to remove the excess of lipids. The supernatants (aqueous crude extract = ACE, 50 mL) were collected, filter sterilized (0.22 μm pore size; Millipore Corp., Bedford, Mass.) and freeze-dried in a Savant-Super Modulyo (ThermoFisher, GA, USA) lyophilizer. ACE dried materials were subsequently weighed and stored at -80 °C.

Fractionation of *C. ensiformis* ACE

C. ensiformis ACE (ACECe) dried was resuspended in dH₂O to obtain a stock solution (250 μg/μL) exhibiting nematocidal activity was transferred to dialysis tubing Spectra/Por 3 with molecular weight cut off of 3.5 kDa (Spectrum Laboratories Inc.) and dialyzed against dH₂O for 24 h at 4 °C. The *C. ensiformis* internal dialysate (IDCe) containing molecules > 3.5 kDa and the external dialysate

(EDCe) containing molecules < 3.5 kDa were lyophilized and stored at -80 °C.

Preparation of commercial plant compounds

Aqueous solutions of the commercial compounds L-canavanine, *cis*- and *trans*-aconitic acids, L-malic acid, citric acid, L-tryptophan, L-methionine, D-pinitol, and S-carboxymethylcysteine were prepared at concentrations of 10 mg/mL and D-glucose at 100 mg/mL. In addition, solutions of palmitic acid and xanthotoxin (10 mg/mL) were also prepared using (10 mg/mL) ethanol and acetone, respectively. All chemicals were purchased from Sigma-Aldrich with purity higher than 98.5%.

Extraction of *M. incognita* J₂ and saprophytic nematodes

To recover eggs, 3-month-old infected tomato (*Lycopersicon esculentum*) roots were cut into 1–2 cm segments and blended for 1 min in a 0.5% sodium hypochlorite solution (Hussey & Barker, 1973). The eggs were collected and transferred to a modified Baermann funnel and maintained at 27 °C. After 48 h, the second stage juveniles (J₂) were counted using Peters slides and an Olympus BH2 B071 microscope. Saprophytic nematodes were obtained from 5-months-old tomato plants that had been previously infected with *M. incognita*. The roots containing several galls in a state of decomposition were cleaned with tap water to remove soil and the nematodes extracted using the methodologies described above.

In vitro nematode assays – *M. incognita* and free living saprophytic nematodes

ACECe (10 μg/μL), EDCe (5 μg/μL), IDCe (5 μg/μL), EDCe heated at 50 °C (EDCe heated) (5 μg/μL) and high-performance liquid chromatography (HPLC) from EDCe fractions (1.2 μg/μL) were diluted in dH₂O. Solutions of commercial chemicals, used as controls, were made up to a final concentration of 1 μg/μL using dH₂O, standards that were not immediately soluble in dH₂O were dissolved in either ethanol or acetone then diluted with dH₂O to final concentrations of 1% (ethanol) and 1% (acetone), respectively. The bioassays were conducted using the final concentration described above for each treatment. Sixty individuals of free living nematodes or J₂ of *M. incognita* were transferred to microcentrifuge tubes and incubated for 48 h at 27 ± 1 °C. Each treatment was replicated three times. Distilled water, ethyl alcohol 70%(EtOH), bovine serum albumin (BSA) and trifluoroacetic acid (TFA) (Sigma-Aldrich Pty Ltd.) were used as controls. After 48 h exposure, the nematodes were observed and counted microscopically with particular attention to their state as either coiled/non-linear (alive) or paralyzed/straightened/dead. The paralyzed nematodes were submitted to a recovery assay. For nematode recovery assays, after 48 h treatment, J₂ nematodes exhibiting a typical dead posture (paralyzed and straightened form) were transferred to 1.5 mL microcentrifuge tubes and centrifuged at 700 × g for 5 min. The supernatant was

discarded and the J_2 nematodes re-suspended in 1.5 mL dH_2O . This procedure was repeated three times. The nematodes were left suspended in dH_2O for a further 12 h. Nematodes were counted microscopically in order to determine either nematocidal or nematostatic activity of the extracts. The statistical analysis of dead and alive J_2 's after water treatment was evaluated by ANOVA and Tukey's mean comparison tests, using SPSS software (SPSS Inc., Chicago, Illinois).

Heating test of the *C. ensiformis* ED

EDCe stock solution previously sterilized (250 $\mu\text{g}/\mu\text{L}$) was incubated in a water bath for 24 h at 50 °C. Then, an aliquot containing 500 μg was selected and submitted for assays against J_2 of *M. incognita*, as described previously. The temperature of 50 °C was chosen after literature search concerning the temperature recorded in the rhizosphere of different plants (Hu & Feng, 2003).

Bacterial assays

The antibacterial activity assays of EDCe (50, 100 and 200 $\mu\text{g}/\mu\text{L}$) were evaluated using a procedure described by Boudart (1989) with modifications (see supplementary). The assays were performed using the bacterium species *Bacillus subtilis* NCTC 8236 kindly provided by the Microbiology Laboratory of Melbourne University.

Fungal assays

The antifungal activity assays of EDCe (50, 100 and 200 $\mu\text{g}/\mu\text{L}$) were conducted according to Abad et al. (1996), with modifications (see supplementary). Fungi (*Colletotrichum gloeosporioides* access 1915, *C. gossypii* var. *cephalosporioides*, *Fusarium solani* access 1624, *Macrophomina phaseolina* access 1496 and *Phytophthora tabacum* (*Phytophthora nicotianae* var. *parasitica*)) were kindly provided by the Microbiology Laboratory of Embrapa – Genetic Resources and Biotechnology, Brasília – DF, Brazil.

Insect assays

In vitro assay of EDCe (50, 100 and 200 $\mu\text{g}/\mu\text{L}$) against *Antonomus grandis* larvae was carried out as described by Monnerat et al. (2000). For *Spodoptera frugiperda*, larval mortality was assessed again at day 5 (Praça, Martins, Batista, & Monnerat, 2004). Each treatment was repeated three times with dH_2O used as a negative control (see supplementary).

Hemolysis assay

Assays were conducted according the supplementary.

Semi-preparative HPLC fractionation

EDCe powder (100 mg) was transferred to a microcentrifuge tube containing buffer A (1 mL, dH_2O /TFA 0.1%) and vortexed

three times for 30 s. The solution was centrifuged at 8000 \times g for 10 min at 4 °C. The supernatant was filtered with a 0.2 μm Minisart RCA filter (Agilent Technologies) and stored at 4 °C.

The resulting sample was analyzed using an 1100 series High Performance Liquid Chromatography (HPLC) system equipped with a multi-wave length detector and Fraction Collector (Agilent Technologies, Santa Clara, US). EDCe (50 μL , 1 $\mu\text{g}/\mu\text{L}$) was injected onto a semi-preparative C_{18} reversed-phase column (Phenomenex, Luna, C_{18} (2), 250 mm \times 10 mm, 10 μm) at room temperature. The mobile phase consisted of 0.1% aqueous TFA (buffer A) and 0.1% TFA in acetonitrile (buffer B). The sample was fractionated using a gradient elution (5% buffer B for 5 min; up to 50% buffer A:50% buffer B for 25 min; up to 100% buffer B for 5 min; 5% buffer B for 1 min; re-equilibration for 11 min) at a flow rate of 2.0 mL/min and collected into 22 individual fractions (F1–F22). Wavelengths of 216, 250 and 280 nm were monitored and fractions were collected automatically on time, using a threshold of 180–200 mAU into a 24 well plate (Corning). The procedure was repeated several times and the corresponding fractions individually pooled, freeze dried and weighed then stored at –80 °C.

GC–MS analysis

Aliquots of EDCe (100 μL , 1 $\mu\text{g}/\mu\text{L}$), HPLC fractions (1 $\mu\text{g}/\mu\text{L}$) and commercial compounds (1 $\mu\text{g}/\mu\text{L}$) were analyzed as their TMS derivatives on an GC–MS system comprised of a Gerstel 2.5.2 autosampler, a 7890A GC and a 5975C quadrupole MS (Agilent Technologies, Santa Clara, US) using the methods of (Hill, Jha, Bacic, Tester, & Roessner, 2013), (see supplementary). Data obtained was processed using Chemstation software (Agilent Technologies, Santa Clara, US). *C. ensiformis* nematocide and nematostatic compounds were identified by comparison with mass spectra data from the libraries GC–MS Metabolomics RTL Library (Agilent Technologies, Santa Clara, US), NIST (<http://www.nist.gov>) and Golm Metabolome Database (<http://gmd.mpimp-golm.mpg.de>, Kopka et al., 2005). The chromatograms and the corresponding mass spectra were deconvoluted using the Automated Mass Spectral Deconvolution and Identification System (AMDIS, NIST, <http://chemdata.nist.gov/mass-spc/amdis/>) software. Quantification of individual compounds was carried out using external standards.

LC–MS analysis

Aliquots of EDCe (40 μL , 1 mg/mL) and HPLC fractions (0.5 mg/mL) were prepared as described previously and were diluted in dH_2O (460 μL), vortexed then transferred to LC vials (Agilent Technologies, Australia). Samples were analyzed using an 6520A Qq-TOF with attached 1200 series LC system comprised of degasser, binary pump, chilled auto-sampler and heated column compartment modules (Agilent Technologies, Santa Clara, US). Instrument conditions were set to: Nebulizer pressure 45 psi, gas flow rate 10 L/min, gas temperature 300 °C, capillary voltage 4000 V, fragmentor 150 V and skimmer 65 V. Both positive and negative ions were monitored in extended dynamic range mode with data collected in m/z 70–1700 amu. Aliquots

(5 μ L) of each sample were injected onto a reversed-phase Zorbax Eclipse XDB (Agilent Technologies, Santa Clara, US), C₁₈ column (2.1 mm \times 100 mm, 1.8 μ m) at a temperature of 50 °C. The mobile phase was prepared as a gradient mixture of 0.1% aqueous TFA (buffer A) and 0.1% TFA in acetonitrile (ACN) (buffer B). The compounds were separated using a 10 min linear gradient from 95:5 v/v buffer A/buffer B to 5:95 v/v buffer A/buffer B at a flow-rate of 0.4 mL/min. Data analysis was performed using the program Mass Hunter Qualitative Software (Agilent Technologies, Santa Clara, US). *C. ensiformis* nematicidal and nematostatic compounds were identified by accurate mass comparison with the METLIN Mass Spectra Library (Agilent Technologies, Santa Clara, US) and where available compared to authentic standards, then corroborated with data obtained by GC–MS.

NMR metabolite identification

Dried sample fractions (F1, F3, F6, F17, F18) (~10 mg) were re-suspended in *d*₄-methanol (0.1 mL) and D₂O (0.1 mL). Then, samples were diluted with sodium phosphate buffer (0.3 mL, pH 7 using DCl/NaOD titration/0.2%, w/v sodium azide). To each sample was added D₂O (0.05 mL) containing 4,4-dimethyl-4-silapentane-1-sulfonic acid (5 mM, DSS). ¹H NMR spectra were collected on an 800-MHz Avance US2 spectrometer (Bruker, Bremen, Germany) then analyzed and identified using the Chenomx 5.1 NMR Suite software package (<http://www.chenomx.com>) (see supplementary).

Greenhouse evaluation

Five samples containing 1 kg of soil were collected from different places of a farm situated around Brasilia-DF – Brazil. Natural soils were prepared according to Jenkins (1964) and analyzed by optical microscopy to certify the absence of *M. incognita* using a conventional taxonomy. Four hundred grams (400 g) of the soil that lacked *M. incognita* were placed into 500 g plastic pots. Tomato plant seedlings (*L. esculentum* Mill. Santa Clara), 15 days post-germination, were transplanted into each pot. Plants were allowed to grow for more than 5 days and then separated into negative control, positive control and EDCe treated. The nematicide Aldicarb (280 mg/kg of soil) was used as positive control and dH₂O was used as negative control. Experiments were performed in triplicate (*n*=3). EDCe solution containing 20 mL (1 mg/mL, final concentration 50 mg/kg of soil) was applied to the soil around each plant. Five hundred (500) *M. incognita* J₂'s were added to each plant, 1–2 cm the soil surface. Tomato plants were then incubated under greenhouse conditions at temperatures varying from 26 to 33 °C. After 45 days of nematode inoculation, the roots were washed, weighed and labeled with β -phloxin (Sigma–Aldrich, 0.015 mg/L) for 20 min. Samples were rated for egg mass index (e.m.i.) using scale of: 0=No galls or egg masses; 1=1–2 galls or egg masses; 2=3–10 galls or egg masses; 3=11–30 galls or egg masses; 4=31–100 galls or egg masses and 5=more than 100 galls or egg masses (Taylor & Sasser, 1978). Data were submitted to analysis of variance and treatment means were compared by Tukey's test (*P*=0.05).

Results

Antagonistic plant seed extract screening assay

In vitro assays using ACE (10 μ g/ μ L) from *T. minuta*, *C. ensiformis*, *M. pruriens*, *C. juncea*, *C. spectabilis* and *C. paulina* seeds were performed against second stage juveniles (J₂) of *M. incognita*. The ACECe elicited the highest level of J₂ mortality, killing 87 \pm 3% of the nematodes after 48 h exposure (Fig. 1). In order to characterize the nematotoxic molecules present in the ACECe, a dialysis procedure was carried out allowing molecular size separation of the plant extract into two different fractions, external dialysate (ED; <3.5 kDa) and internal dialysate (ID; >3.5 kDa).

A second assay against J₂ of *M. incognita* demonstrated that molecules from EDCe (5 μ g/ μ L) produced 96 \pm 3% J₂ larvae mortality, while IDCe compounds showed no lethal activity (Fig. 2). These results indicated that the toxic effect of *C. ensiformis* was due to molecules with low molecular weight, found mainly in the EDCe.

Heating tests using EDCe solution (5 μ g/ μ L) that had been heated at 50 °C for 24 h demonstrated a high level of toxicity retained against J₂ of *M. incognita* with 96 \pm 2% of the J₂ larvae killed after 48 h of exposure (Fig. 2).

Non-target organism assays – saprophytic nematode, bacteria, fungi and insects assays

In vitro assay for free living saprophytic nematodes using 5 μ g/ μ L of EDCe demonstrated a mortality rate of only 6 \pm 3%, compared with 96 \pm 3% for J₂ of *M. incognita* (Fig. 3 and Table 1). Assays using EDCe against the agriculturally relevant fungi *C. gloeosporioides* (access 1915), *F. solani* (access 1624), *M. phaseolina* (access 1496) and *P. tabacum* var. *Parasitica* did not show any growth inhibition halos around discs containing 250 μ g/5 μ L, 500 μ g/10 μ L and 1000 μ g/20 μ L of EDCe. Indeed, all fungi grew normally, covering the full Petri dish after 96 h exposure, except around discs where the antibiotic nystatin was used as a positive control (Table 1). The same concentrations of EDCe also failed to inhibit the growth of the bacteria, *B. subtilis*, after 16 h incubation. Similar to fungus inhibition assays, the rings of clearing (halos) were only observed around discs containing the antibiotic sirodesmin that was used as a positive control (Table 1).

Furthermore, no insecticidal effect was observed when the agricultural pests *A. grandis* and *S. frugiperda* insect larvae were grown on an artificial diet containing 200 μ g/ μ L of EDCe. After 7 days incubation, the larvae of both insects exhibited the same physiological characteristics (weight, size, color and mobility) and were indistinguishable from those used in the control (Table 1); longer term effects were not measured.

Cytotoxic evaluation

EDCe did not show any hemolytic activity when in the presence of either total bovine blood or bovine red blood cells at concentrations varying from 0.125 to 16 mg/mL (see supplementary Fig. S1).

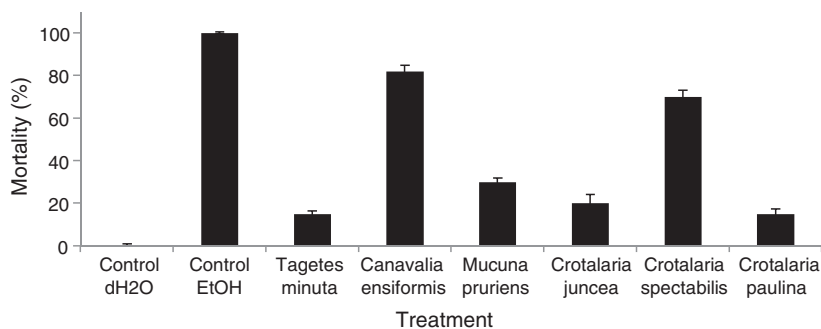


Figure 1 Nematode assay showing the effect of aqueous crude extracts (ACE) of antagonistic plant seeds (10 $\mu\text{g}/\mu\text{L}$) on second stage juveniles (J₂) of *M. incognita* after 48 h exposure with dH₂O and ethyl alcohol 70% (EtOH) used as controls. Bars indicate the percentage of dead nematodes; error bars indicate standard deviation.

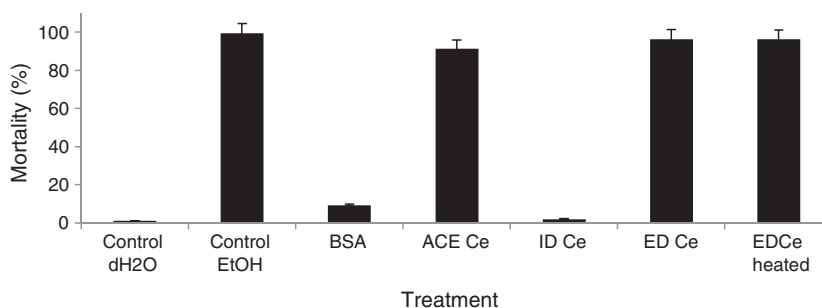


Figure 2 Nematode assay exhibiting the effect of *C. ensiformis* ED fraction (EDCe) (final concentration 5 $\mu\text{g}/\mu\text{L}$) and ID fraction (IDCe) (final concentration 5 $\mu\text{g}/\mu\text{L}$) against J₂ of *M. incognita*. dH₂O, ethyl alcohol 70% (EtOH), bovine serum albumin (BSA) with the aqueous crude extract of *C. ensiformis* (ACECe) used as controls. ED solution 5 $\mu\text{g}/\mu\text{L}$ heated at 50 °C. Bars represent the percentage of dead nematodes; error bars indicate standard deviation. Assays were performed in triplicate with nematodes exposed for a period of 48 h.

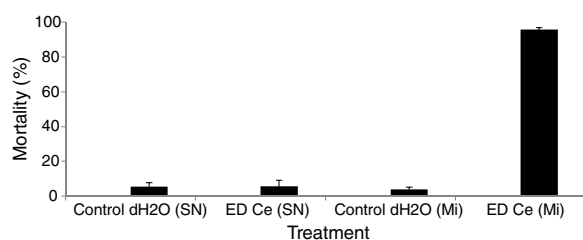


Figure 3 Nematode assay showing the effect of *C. ensiformis* ED fraction (ED Ce) (5 $\mu\text{g}/\mu\text{L}$) against saprophytic nematode (SN) and *Meloidogyne incognita* (Mi). Distilled water was used as control for both nematode. Error bars indicate standard deviation. Assays were performed in triplicate with nematodes exposed for a period of 48 h.

Light microscopy

The anatomy of J₂ of *M. incognita* exposed to EDCe was examined by light microscopy and showed disruption of the normal anatomy (Fig. 4A, B) with the formation of structures similar to vacuoles along abnormally straightened J₂ body (Fig. 4C, D).

Greenhouse evaluation

To measure the effectiveness of treating soil with EDCe to inhibit J₂ infection and progression to later life stages tomato plants were infected. Status of the nematodes was evaluated by comparing the effect of a commercial nematicide (Aldicarb, used as positive control) and dH₂O (used as negative control) with EDCe under simulated conditions in a greenhouse. The treatment with EDCe showed a remarkable reduction in egg mass number. Egg masses decreased by 82% for the EDCe treatment and 94.2% for the positive control employing the commercial nematicide in comparison to the negative control using dH₂O (Fig. 5). On average, only 18 egg masses (egg mass index (e.m.i.) = 3) were observed with the treatment of EDCe against 6 egg masses for the chemical nematicide (e.m.i. = 2) and 103 for dH₂O (e.m.i. = 5) (Fig. 5).

Purification and analysis of bioactive fractions

The purification and fractionation of EDCe was performed using a semi-preparative C₁₈-RP/HPLC column with a linear gradient of 5–95% (TFA/ACN) at a flow rate of 2 mL/min. Fractionation was repeated 40 times with a total of 87 mg recovered from 200 mg of crude EDCe in 22 chromatographic

Table 1 Summary table of *in vitro* non-target organisms assays using different concentrations of *C. ensiformis* ED (EDCe) against fungi, insect larvae, nematodes and bacteria. All assays were conducted in triplicate.

	Pathogens	µg/µL of <i>C. ensiformis</i> ED/assay	Activity
Fungi	<i>Colletotrichum gloeosporioides</i>	50, 100, 200	None – normal growth
Fungi	<i>Fusarium solani</i>	50, 100, 200	None – normal growth
Fungi	<i>Macrophomina phaseoline</i>	50, 100, 200	None – normal growth
Gram + bacteria	<i>Bacillus subtilis</i>	50, 100, 200	None – normal growth
Insect larva	<i>Anthonomus grandis</i> (larvae)	200	None – normal development
Insect larva	<i>Spodoptera frugiperda</i> (larvae)	200	None – normal development
Nematode	<i>Saprophytic nematode</i>	100	None
Nematode	<i>Meloidogyne incognita</i>	100	Nematicidal

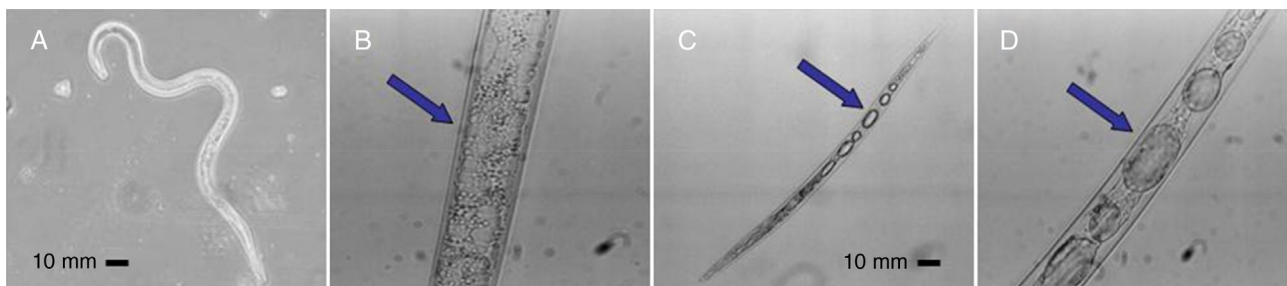


Figure 4 Light microscopy illustrating the effect caused by *C. ensiformis* ED (EDCe) on *M. incognita* J₂. (A) J₂ before addition of (EDCe) showing typical curled shape. (B) J₂ intestinal region before addition of (EDCe), arrow indicates normal morphology. (C) J₂ 48 h after addition of (EDCe), showing linear and straightened profile, arrow indicates vacuoles. (D) J₂ intestinal region 48 h after addition of (EDCe), arrow indicates vacuoles and breakdown of normal morphology.

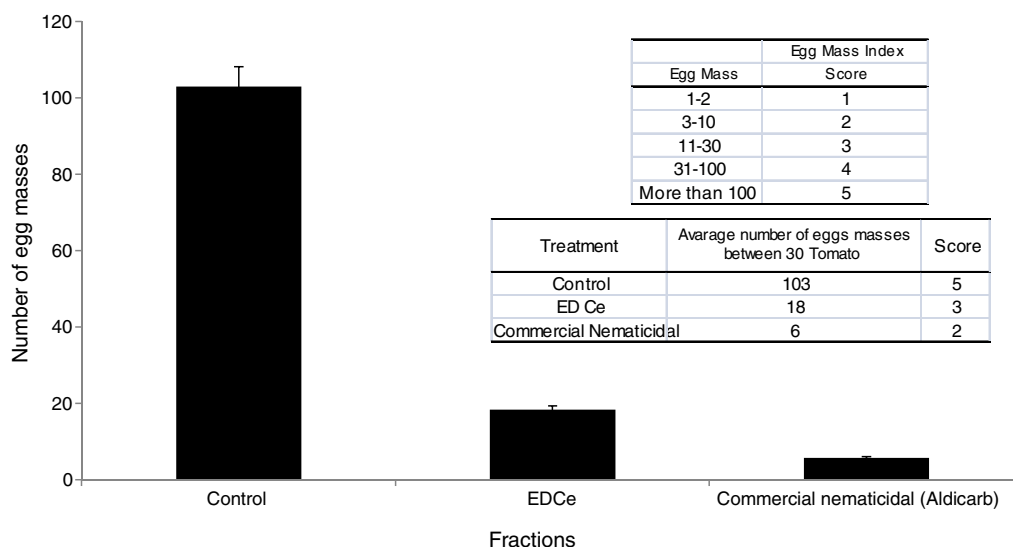


Figure 5 Evaluation *C. ensiformis* ED (EDCe) soil treatment (50 mg/kg of soil) to limit *M. incognita* second stage juvenile (J₂) infection of tomato plants and ability to progress to later life stages under greenhouse conditions. Bars represent the number of egg masses observed for tomato roots after the period of treatment. The experiment was conducted in triplicate with dH₂O and the commercial nematicidal Aldicarb (280 mg/kg of soil) used as positive and negative controls, respectively (n = 3). The egg mass index was used to evaluate the effectiveness of *C. ensiformis* external dialyzate.

fractions (F1–F22), representing a mass recovery of 43%. Each fraction (500 µg) was individually tested against *M. incognita* J₂'s (Fig. 6A). Only fractions F1, which comprised 11% by mass of the total composition of the EDCe, F3 (14% of EDCe), F6 (0.35% of EDCe), F17 (0.27% of

EDCe) and F18 (0.05% of EDCe) demonstrated the ability to paralyze and linearly straightened above 95 ± 3% the nematodes from a typical coiled or non-linear shape after 48 h exposure (Fig. 6B). Paralyzed nematodes were then transferred to water for a further 12 h (recovery assay).

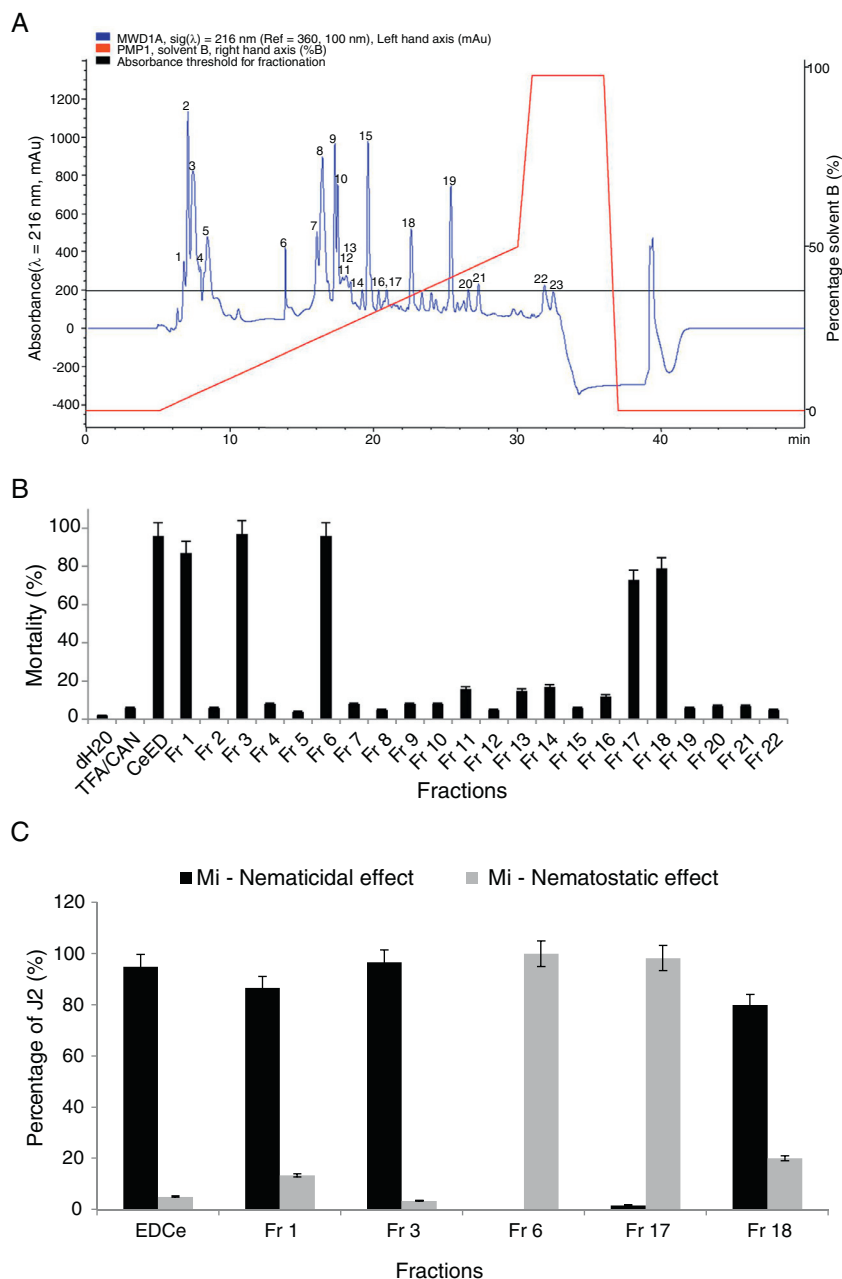


Figure 6 (A) HPLC Chromatogram of semi-preparative C18 reversed-phase separation (Phenomenex, Luna, C₁₈ (2)), (250 mm × 10 mm, 10 μ m) of *C. ensiformis* ED (EDCe), using 0.1% aqueous TFA (Solvent A) and 0.1% TFA in acetonitrile (Solvent B) at room temperature. Blue line indicates UV absorbance (mAU, left axis) at λ = 216 nm, red line indicates percentage solvent B (right axis), black line indicates 200 mAU cut-off limit for automatic fraction collection. The profile exhibits a selection of the 22 fractionated peaks F1-22. (B) Nematode assay comparing ability of 500 μ g of each isolated fraction to paralyze J₂ of *M. incognita*, results show the fractions (F1, F3, F6, F17 and F18) to be highly active, (n = 3), 60 J₂ were used per replicate; error bars indicate percentage standard deviation. (C) Recovery assays where J₂'s from *M. incognita* were transferred to water after treatment with respective fractions, results confirm nematicidal effect for fractions F1, F3 and F18 (dark gray) where J₂ did not recover the movement, and nematostatic activity for fraction F6 and F17 (light gray) where J₂ recovered their motility (n = 3), error bars indicate standard deviation.

Results showed that 90% of J₂'s in fractions F1, F3 and F18 remained paralyzed, confirming the nematicidal activity. For F6 and F17 around 87% of J₂ exposed to the treatments recovered their motility, indicating a nematostatic activity (Fig. 6C).

Metabolite profiling and identification

GC-MS analyses were performed using the EDCe unfractionated and also the identified nematicide/nematostatic fractions (F1, F3, F6, F17 and F18) after HPLC separation

of the ED. Greater than 170 individual peaks were readily identified in the resulting chromatograms of EDCe revealing the presence of a large number of metabolites eluting over the temperature gradient. Chromatograms of the active fractions were superimposed and invariably exhibited the occurrence of more than one peak that overlapped with those found in the EDCe (see Fig. S2 supplementary).

A total of 158 individual peaks were found within the EDCe, of which a total of 52 compounds belonging to different chemical classes were identified by library matching, with the further 106 peaks remaining unknowns in the summary of peaks in each fraction after common contaminants and background ions were removed. Analysis of nematocidal and nematostatic fractions found a total of 16 unknowns and 18 identified sugars and amino acids in F1; F3: 13 unknowns and 15 identified amino acids and sugars; F18: 13 unknowns and 7 identified fatty acids, aromatic amino acids and xanthotoxin; F6: 14 identified amino acids and organic acids, with 16 unknowns; F17: 17 unknowns and 6 identified fatty acids, aromatic amino acids and S-carboxymethylcysteine (see supplementary Table S1). Identified compounds obtained from GC-MS mass spectra of EDCe as well as HPLC separation fractions are described in the supplementary section (Tables S2 and S3).

LC-MS analyses were also performed on the same fractions. Mass spectra generated from these fractions, in both negative and positive ion mode were compared with the METLIN mass spectral library (see Table S4 supplementary). Several compounds of distinct chemical classes were detected, but only those showing matches above 70% were considered for further comparison; within F1: 3 sugars and asparagine were identified; F3: glutamic acid and N-acetylserine; F6: valine, *cis/trans*-aconitic acid, and citric acid; F17: phenylalanine; F18: tryptophan (see Table S4 supplementary).

Furthermore, profiling of nematotoxic fractions was undertaken using NMR spectroscopy. The resulting spectra were compared against the Chenomx NMR metabolite database to further confirm the presence of the identified metabolites from GC-MS and LC-MS analyses. Each fraction displayed a complex signal demonstrating the presence of many metabolites. Within F1: included common amino acids - glycine, asparagine and a variety of sugars; F3: further amino acids, sugars and L-canavanine; F6: organic acids and valine; F17: phenylalanine and S-carboxymethylcysteine; F18: some amino acids, xanthotoxin (supplementary Table S5).

After the compounds identification by GC-MS, LC-MS and ^1H NMR analyses an extensive literature was performed in order to identify any known biological function of the compounds detected and identified. Furthermore some of the compounds chosen were obtained commercially with high purity degree and they were used to validate the nematotoxic activity against *M. incognita* J2.

Activity testing for commercial chemical compounds identified

To verify the effectiveness of the isolated compounds previously identified in EDCe fractions on J₂ of *M. incognita*,

assays were carried out using commercially sourced, highly purified materials. Hence, D-glucose at a final concentration of 0.26 $\mu\text{g}/\mu\text{L}$ paralyzed the majority of nematodes after 48 h exposure (Fig. 7A). In the recovery assay, 98% of J₂ recovered their motility confirming the nematostatic activity for glucose at the applied concentration (Fig. 7B). However, D-glucose at concentration of 0.5 $\mu\text{g}/\mu\text{L}$ exhibited a nematocidal effect killing more than 90% of J₂ after 48 h exposure (Fig. 7B). D-Pinitol was completely ineffective against *M. incognita* J₂ juveniles after 48 h (Fig. 7A). Similarly, L-canavanine did not show any nematotoxic activity at a concentration of 0.26 $\mu\text{g}/\mu\text{L}$ after 48 h exposure (Fig. 7A). In contrast, at a concentration of 0.5 $\mu\text{g}/\mu\text{L}$, 50% of J₂ remained paralyzed after the recovery assay, confirming a discrete nematocidal activity and a potential toxic threshold (Fig. 7B). Among the organic acids, malic, citric, *cis*-aconitic, *trans*-aconitic and the fatty palmitic acid only the *trans*-aconitic and palmitic acid were able to paralyze 98% and 90% of J₂ at concentrations of 0.5 $\mu\text{g}/\mu\text{L}$ after 48 h exposure (Fig. 7A). The remaining organic acids identified only paralyzed a very low percentage of J₂ (Fig. 7A). *Trans*-aconitic acid at concentration of 0.5 $\mu\text{g}/\mu\text{L}$ demonstrated a nematocidal activity of 97% while malic, citric and *cis*-aconitic acids exhibited only a nematocidal effect of 55%, 68% and 65%, after the recovery assay (Fig. 7B). Palmitic acid showed a nematostatic effect for both concentrations evaluated with above 90% of J₂ recuperating their mobility after the recovery assay (Fig. 7B). The amino acids L-phenylalanine, L-methionine and L-tryptophan were completely innocuous for both concentrations (Fig. 7A). Inversely, the compound S-carboxymethylcysteine paralyzed around 90% of J₂ for both concentrations tested after 48 h exposure (Fig. 7A). Following recovery assay the majority of J₂ recuperated their mobility confirming the nematostatic effect (Fig. 7B). Approximately 87% of J₂ treated with xanthotoxin were paralyzed after 48 h exposure (Fig. 7A). The paralyzed J₂ did not recover their mobility after the recovery assay confirming the nematocidal activity (Fig. 7B). The control, 50 mM Tris/HCl pH 8, exhibited a nematostatic activity while 50 mM acetic acid pH 5 showed a nematocidal effect after recovery assay and have been used to certify the pH influence on the plant material activity (ACE, ED, ID, HPLC fractions and commercial compounds) (Fig. 7B).

Discussion

This work explored an alternative strategy to be used in conjunction with the other current nematode control methods. A traditional bioprospecting approach coupled to modern high throughput metabolomics methods was adopted aiming the identification of nematotoxic metabolites from antagonistic plants.

It is known that natural products target a wide variety of proteins and other biological components with specific purposes, like some leguminous nematode-antagonistic plant seeds that are a rich source of natural nematocidal and nematostatic compounds. The screening test demonstrated that the ACECe has an effective nematocidal activity against second stage juveniles (J₂) of *M. incognita*. A similar result with other plant species was reported by (Khurma & Man-gotra, 2004) where aqueous extracts of *Trigonella foenum*

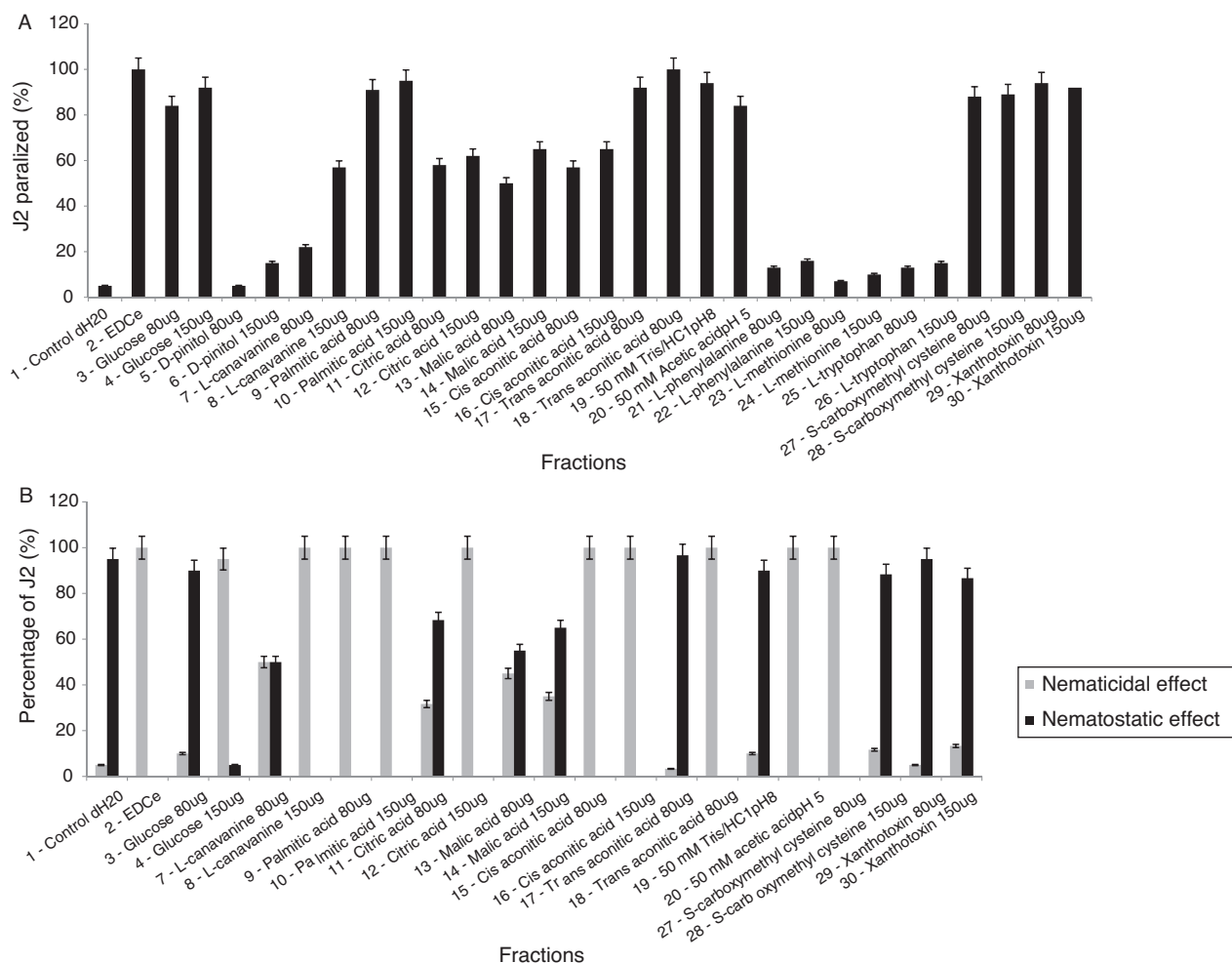


Figure 7 (A) Nematode assay exhibiting the ability of commercial compounds to paralyze second stage juveniles (J_2) of *M. incognita* after 48 h exposure ($n=3$), 60 J_2 were used per replicate, error bars indicate standard deviation. (B) Recovery assays showing control (white fill), nematicidal (dark grey fill) and nematostatic (light grey fill) effects on J_2 ($n=3$), error bars indicate standard deviation.

graceum, *Sesbania sesban*, *Albizia lebbeck*, *Cassia fistula* and *Milletia pinnata* were responsible for the highest *M. incognita* J_2 mortality (90–97%). In addition, we found that small molecules extracted from *C. ensiformis* seeds were related to the observed toxic effects as pointed by the EDCe mortality of about $96 \pm 3\%$. Previous reports indicated that a variety of common metabolites were toxic to several nematode species, including the non-protein amino acid L-canavanine that is naturally abundant in seeds of *C. ensiformis* (Birch, Fellows, Geoghegan, Robertson, & Watson, 1992; Rosenthal, 1990); the L-3,4-dihydroxyphenylalanine which is active against *M. incognita* and *Heterodera glycines* (Barbosa, Barcelos, Demuner, & Santos, 1999; Osman, 1993); and L-arginine and L-glutamic acid against *M. javanica*. Talavera and Mizukubo (2005) revealed the action of L-methionine against *M. incognita*, while Oliveira et al. (2009) demonstrated the activity of cysteine on *M. exigua* *in vitro* and *in vivo*.

J_2 larvae from *M. incognita* showed remarkable anatomic modifications with the development of anomalous features in the form of large vacuoles after 48 h of exposure to the

EDCe (see Fig. 4). This alteration is potentially related to the presence of toxic compounds that are able to cross the nematode cuticle, interfering in vital processes, which may include enzymatic, nervous and respiratory systems. Alternatively the juveniles' death might be linked to dehydration through the existence of an osmotic potential caused by high sugar concentration in the EDCe. It was demonstrated that solutions containing 0.26–0.5 $\mu\text{g}/\mu\text{L}$ sucrose reduced larvae motility, leading to morphological alterations and cell death of *M. javanica* and *M. incognita* juveniles (Santiago, Homechin, Montalvan, & Krzyzanowski, 2005).

EDCe was also tested against fungi and bacterium species (Table 1). A range of concentrations up to 50 $\mu\text{g}/\mu\text{L}$ of EDCe could not inhibit the growth of either *C. gloeosporioides*, *F. solani*, *M. phaseolina*, *P. tabacum* or *B. subtilis*. This absence of activity could be associated with a concentration of a specific compound present in the EDCe. Similar results were observed for extracts of *Plantago lanceolata* and *P. rugelii*, which were able to kill *M. incognita* larvae, but had no toxicity toward *Enterobacter cloacae*, *Pseudomonas fluorescens*, *Trichoderma virens*, *Fusarium oxysporum*,

Phytophthora capsici, *Pythium ultimum* and *Rhizoctonia solani* (Meyer et al., 2006). Besides no insecticidal effects were observed when *A. grandis* and *S. frugiperda* larvae, both significant agricultural pests, were grown on an artificial diet containing 200 µg/µL of EDCe. Concanavalin A (lectin), vicilin, canatoxin and urease present in seeds of *C. ensiformis* are found to be very toxic against different classes of insects (Carlini & Grossi-de-Sá, 2002). However, these polypeptides were removed during the dialysis procedure. Since only 200 µg/µL of EDCe were used in our bioassays, the concentration of L-canavanine was too low to affect the growth of both larval insects. In addition, an *in vitro* assay using EDCe at a concentration of 100 µg/µL killed only 5% of free living nematodes compared to the 90% mortality of *M. incognita*. The low mortality rate of saprophytic nematodes may be associated with their cuticles. The cuticle is a complex structure of plates, fibers, and several layers of proteins. It can differ dramatically between species and also at their stage of development (Bird & Bird, 1991).

In vitro cytotoxic evaluation using a hemolysis assay demonstrated that the EDCe has no hemolytic activity against bovine blood or isolated bovine red blood cells indicating that these molecules possibly are not risky to non-targeted mammalian organisms (see supplementary Fig. S2). Moreover, it was also shown that the EDCe after being incubated at 50 °C for 24 h was able to kill 96% of the phytoparasites. The thermostability of any potential nematotoxic compounds is an essential physical characteristic to be determined as any compound must be stable in the prevailing environment. This result reflects the thermostability of the active compounds present in the sample. Moreover, it is important to highlight that the experiment was conducted at a higher temperature than the average temperatures of soil layers where roots of different cultures, including cotton, soy, coffee, sugar-cane and other important crops are grown (Hu & Feng, 2003).

The EDCe metabolites and their ability to inhibit the infective J₂ stage were evaluated by simulating field conditions at greenhouse conditions. The egg mass index (Taylor & Sasser, 1978) was used to measure the ability of the J₂ stage of *M. incognita* to infect tomato plant roots and progress to later life stages. Results showed a remarkable 82% reduction in the number of egg masses from *M. incognita* infection of tomato plants harvested 45 days after inoculation to the treatment using EDCe against 94.2% to the commercial nematicide Aldicarb. Furthermore, it was not observed visual modifications to the tomato plant along the experiment.

With effectiveness toward J₂ of *M. incognita* determined, attention turned to identification of the active metabolites. To achieve that an active bioassay-guided HPLC purification and fractionation strategy was employed using EDCe. Metabolites were separated into 22 fractions which were submitted to *in vitro* assays against *M. incognita* J₂. Significant activity was observed for the fractions F1, F3, F6, F17 and F18. Two effects were observed: a nematicide effect for F1, F3 and F18 and a nematostatic effect was demonstrated for F6 and F17 fractions against *M. incognita* J₂. The variation in efficacy detected for each fraction could either be due to the presence of different compounds in each fraction.

Finally, metabolite profiling of plant extracts integrating GC-MS, LC-MS, and NMR technologies combined with

a thorough literature search represented a powerful and reliable approach providing substantial information of the chemical composition of *C. ensiformis* fractions. In this way, the HPLC nematotoxic fractions of *C. ensiformis* allowed the identification of components belonging to distinct chemical classes. The nematicide activity observed for F1 on *M. incognita* juveniles might be correlated with the osmotic effect inflicted by the high content of different sugars, such as D-glucose and D-pinitol. Literature searching indicated the sugar D-glucose present in F1 and F3 to be nematostatic or nematicidal (Santiago et al., 2005). D-Pinitol, a bioactive carbohydrate located in F1 has been reported as a larvicidal molecule (Chaubal et al., 2005). Despite the high effectiveness of D-pinitol against different insect larvae classes, no effect was noted when its commercial form was tested against *M. incognita* juveniles using a higher concentration than the active F1, excluding D-pinitol as the active compound responsible for causing nematodes death. However, the *in vitro* assay using 0.26 µg/µL of commercial D-glucose against *M. incognita* juveniles demonstrated the same killing effect observed for the crude F1. Moreover, similar results published by Santiago et al. (2005) also demonstrated that solutions containing 0.26–0.5 µg/µL D-glucose decreased the motility and ultimately killed *M. javanica* and *M. incognita* juveniles in experiments conducted *in vitro*, corroborating our results. A nematicide activity was also observed for F3 after 48 h exposure. Both D-glucose and L-canavanine were confirmed in F3 by NMR, with L-canavanine by far the most abundant compound found within the fraction. L-canavanine is reported as a remarkable insecticide and at low concentrations and this non-proteinogenic amino acid can also kill nematodes from different genera (Birch et al., 1992). Intriguingly, the commercial form of this compound failed completely at a concentration of 0.26 µg/µL and killed only 50% of *M. incognita* juveniles at higher concentrations (0.5 µg/µL). The nematostatic activity caused by F6 is possibly associated to the high content of the organic acids, *cis* and *trans*-aconitic acids, malic acid and mainly citric acid. The organic acids found in F6: *cis* and *trans*-aconitic act as leishmanicides (Kar, Kar, Bhattacharya, & Ghosh, 1993) while citric acid is reported to be weakly nematotoxic (Shemshura et al., 2016). The mixture of these compounds is able to dramatically decrease the pH making the environment very acidic and consequently affecting the nematodes behavior. In this sense, two internal controls were used to evaluate the action of acidic and alkaline pH on J₂ of *M. incognita*. In the case of alkaline pH (50 mM Tris/HCl pH 8) a nematostatic activity was observed while for acidic pH (50 mM acetic acid pH 5) a nematicide activity. *In vitro* assay results using these compounds individually at 0.26 µg/µL showed exactly the same result observed for F6. Nevertheless, when the concentration of the organic acid *trans*-aconitic acid and fatty acid palmitic acid was increased the juveniles were not able to recover any of their motility, confirming a nematicidal activity. It is important to note that nematodes belonging to distinct species behave differently depending upon the pH environment. Yet, the action of these acids appears to be dose dependent as demonstrated by *in vitro* assay. Fraction 17 exhibited a nematostatic activity. A high content of phenylalanine and S-carboxymethylcysteine with lower concentrations of palmitic acid were found in this fraction.

Some amino acids and palmitic acid are known to be very toxic to different nematode species (Oliveira et al., 2009).

In vitro assays using commercial phenylalanine and palmitic acid were innocuous against *M. incognita* J₂. Paradoxically, commercial S-carboxymethylcysteine demonstrated a nematostatic activity paralyzing about 100% of the juveniles at 0.5 µg/µL concentration. This result indicated that this cysteine derivative is the compound involved with the nematostatic effect exhibited by F17. Similarly, Oliveira et al. (2009) demonstrated the activity of cysteine on *Meloidogyne exigua* in experiments conducted *in vitro* and in greenhouse. The nematocidal activity showed by F18 against juveniles of *M. incognita* could be associated with xanthotoxin, a plant toxin present in this fraction. Xanthotoxin exhibits a noteworthy action on insects and mollusks and also acts as an antifedant. *In vitro* assay using commercial xanthotoxin was able to demonstrate a 95% kill of juveniles to 0.5 µg/µL. This result indicated that the activity observed for F18 may be related to the action of this compound.

Conclusion

Amongst the antagonistic plants seed aqueous crude extract, *C. ensiformis* exhibited the highest nematocidal activity. Its EDCe also demonstrated to be very effective against *M. incognita* (J₂), but did not adversely affect beneficial saprophytic nematodes, fungi, bacterium and insect pests. Hemolysis tests showed that EDCe was not able to disrupt bovine red blood cells and when heated at 50 °C retained a high level of toxicity against *M. incognita*. Moreover, the EDCe decreased the number of *M. incognita* eggs masses by 82% at experiments conducted at greenhouse conditions. The metabolite profiling of *C. ensiformis* seeds using a comprehensive approach based on GC/MS, LC/MS, and ¹H NMR technologies and a thorough literature search provided a consistent and substantial amount of information concerning the nematotoxic compounds present in this leguminous plant. The nematocidal compound D-glucose, L-canavanine and xanthotoxin, as well as the nematostatic compounds *trans* aconitic acid, citric acid, palmitic acid and S-carboxymethylcysteine used against *M. incognita* larvae, were identified using this integrated approach. These results corroborate the potential of ACECe as a source of nematotoxic compounds.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.biori.2017.10.003](https://doi.org/10.1016/j.biori.2017.10.003).

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