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Short communication

Flame soil disinfestation: A novel, promising, non-chemical method to control soilborne nematodes, fungal and bacterial pathogens in China

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A B S T R A C T

Flame soil disinfestation (FSD) is a novel, promising non-chemical method to control soilborne nematodes, fungal and bacterial pathogens in China. The efficacy of FSD on soilborne nematodes, fungal and bacterial pathogens was evaluated during two field trials. The field trials revealed that the treatment with FSD once (FSD1) and treatment with FSD twice (FSD2) sharply reduced the total number of soilborne nematodes (>95%) and completely controlled *Meloidogyne incognita* in the soil. Both FSD1 and FSD2 also provided promising efficacy against soilborne *Fusarium oxysporum* (>44%), *Phytophthora* spp. (>47%) and *Ralstonia solanacearum* (>67%) on media. However, there was no significant difference between FSD1 and FSD2 in controlling soilborne nematodes, fungal and bacterial pathogens ($P = 0.05$). Currently, there are two challenges to distribute the technology in China: its high cost and relatively low efficiency because of the low speed of application compared with soil chemical fumigation. Despite the drawbacks, FSD is still promising in organic agriculture for controlling soilborne nematodes, fungal and bacterial pathogens.

1. Introduction

In China, the area of protected cultivation of crops has grown in recent years, and the total area is currently over 3,400,000 ha. Soilborne nematodes, fungal and bacterial pathogens exhibit strong yield depressing potential because of the continuous crop rotations (Cao, 2003; Giannakou and Anastasiadis, 2005). Therefore, soil disinfestation is an essential method for controlling soil-borne nematodes, fungal and bacterial pathogens to prevent their damage and maintain production at the required levels. Soil disinfection is commonly implemented before planting by either using soil fumigants or non-chemical methods (Labrada, 2007).

Methyl bromide (MB) has been the most popular pre-plant soil fumigant against soil-borne nematodes, fungal and bacterial pathogens in China (Cao, 2003). However, MB had been totally phased out except for the Critical Use Exemptions (CUE) in ginger, and Quarantine and Pre-shipment (QPS) in China since 1 January 2015, due to the detrimental effects on stratospheric ozone (Bell, 2000; TEAP, 2014; UNEP MBTOC, 2014). 1,3-dichloropropene (1,3-D) (Qiao et al., 2010, 2011; Wang et al., 2009), chloropicrin (Pic) (Mao et al., 2014a; Yan et al., 2012), sulfuryl fluoride (SF) (Cao et al., 2014), 1,3-D/Pic (Ji et al., 2013; Wang et al., 2013), 1,3-D/dazomet (DZ) (Mao et al., 2012), dimethyl disulphide (DMDS)/DZ (Mao et al., 2014b), and other soil fumigants have been tested as promising chemical alternatives to MB for crop production in China. However, the major drawback of chemical soil fumigants is the high toxicity of the active substances to human and the environment. Furthermore, long waiting periods are needed before replanting.

Currently, non-chemical methods include resistant cultivars (Avilés et al., 2009), substrates (Maršić and Jakše, 2010), grafting (King et al., 2008), biofumigation (Hansen and Keinath, 2013), solarisation (Katan and Gamliel, 2012), hot water treatments (Fujinaga et al., 2005; Tateya, 2001), steam (Gilardi et al., 2014), anaerobic soil disinfestation (ASD) (Butler et al., 2012, 2014), systemic acquired resistance (SAR) (Walters et al., 2005), biological control (Sánchez-Téllez et al., 2013) and organic amendments (Ji et al., 2012). However, there is limited information about flame

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soil disinfestation (FSD) in the world.

As a physical soil disinfestation technique, FSD treatment is a novel promising method of soil disinfestation in the greenhouse and in the field in China. There is no report in the literature on the ability of FSD treatment to control soilborne nematodes, fungal and bacterial pathogens in China.

The following work was initiated to determine the effects of FSD on root-knot nematodes (*Meloidogyne incognita* (Kofoid and White) Chitwood), key soil-borne fungi (*Fusarium oxysporum* Schlechtend.:Fr. and *Phytophthora* spp.) and bacteria (*Ralstonia solanacearum* (Smith) Yabuuchi et al.) in two field trials.

2. Materials and methods

In 2013 and 2014, two field trials were conducted in Anqiu, Shandong, and Bengbu, Anhui, respectively. The two farms are both facing problems caused by heavy infestations of soilborne nematodes, including *M. incognita*, soil-borne fungi, and other pests. The relevant details are given in Table 1. The organic carbon content was determined by wet oxidation using the Walkley and Black method (Nelson and Sommers, 1985). The pH was measured in a 1:2.5 soil to H_2O extract.

The FSD machine was manufactured by Anhui Yuanda Machinery Manufacturing Co., Ltd (Bengbu, Anhui, China). There are three main parts: the force of traction, the soil crushing part and the high temperature part. The entire structure diagram and working photo of the flame soil disinfestation (FSD) machine are given (Figs. 1 and 2.). According to the information provided by the manufacturer, the high temperature part includes two rows of flame tubes, a pressure tank, a gas supply line and a high temperature oven. FSD uses compressed natural gas (CNG) as the main fuel, and the flame temperature at the nozzle of flame tubes could be increased up to 1200 °C; the temperature in the oven is approximately 400–600 °C. For easier understanding of the key structures of the machine, the map of two rows of flame tubes and the soil crushing part was separately given (Fig. 3.). The machine works in the following manner: the machine is driven by a small tractor, and the soil is crushed (soil depth: about 20–25 cm) and brought to the place near the nozzle of the flame tubes (the soil could be heated in 2–3 s); finally, the soil falls to the ground (the current temperature is approximately 50–70 °C), and then the next cycle begins (Fig. 2.). The forward speed of operation of the FSD machine was 0.12–0.18 km/h (machine width: about 160 cm), so the rate of treatment was 0.0192–0.0288 ha/hr. The power of the machine was 51.5–58.8 kW, and the total cost of treatment with FSD once was about 30, 000 to 40, 000 RMB Yuan per ha of land treated.

The treatments tested in each trial were FSD treated once (FSD1), FSD treated twice (FSD2) and an untreated control. The treatments were designed as randomized blocks with three replicates. Each treated plot was 50 m^2. Trial I (Anqiu, 36°19′40.2″N, 119°3′58.4″E) was performed on 23 October 2013, and trial II (Bengbu, 32°52′28.9″N, 117°18′1.2″E) was performed on 6 May 2014.

The population densities of soilborne nematodes, fungal and bacterial pathogens were determined after soil treatments from soil samples at depths of 0–20 cm. Soil from each plot was sampled from 5 spots along a diagonal line across each plot. The total number of soilborne nematodes and root-knot nematodes were determined by the method Liu (2000). Soilborne *F. oxysporum* and *Phytophthora* spp. were assessed using the methods employed by Komada (1975) and Masago et al. (1977), respectively. *R. solanacearum* was isolated from the soil quantitatively based on the method described by Kelman (1954).

The efficacy in controlling nematodes, fungi or bacteria was calculated according to the following equation:

$$Y = \frac{X_1 - X_2}{X_1} \times 100,$$

where Y is the control efficacy, X_1 is the population in the untreated plots, and X_2 is the population in the treated plots.

Data were analysed for ANOVA with SAS (SAS, version 8.0 for Windows). Data for the populations of soilborne nematodes, fungi or bacteria were transformed as necessary (square root transformations for small numbers [<100] and $\log_{10}$ for large numbers [>100] for statistical analyses), but all data were reported as non-transformed values. Significant differences among means were determined by Fisher's LSD test at $P = 0.05$ (Csinos et al., 1997; Steel and Torrie, 1960).

3. Results

3.1. Soilborne nematodes

The untreated plots in trial I (in 2013) and trial II (in 2014) were heavily infested with soilborne nematodes, including *M. incognita* (Table 2). Soilborne nematode and *M. incognita* levels were both significantly higher in the untreated plots compared with the plots which received the FSD treatments. FSD2 provided better control efficacy on the total soilborne nematodes; however, the results of two FSD treatments did not differ significantly ($P = 0.05$).

FSD1 treatment reduced the total soilborne nematode levels in trial I and trial II by 95.0% and 96.6%, respectively. FSD2 treatments reduced the total soilborne nematode levels in trial I and trial II by 99.0% and 100.0%, respectively. Both FSD1 and FSD2 treatments completely controlled *M. incognita*.

3.2. Soilborne fungi

The untreated plots were heavily infested by *F. oxysporum* and *Phytophthora* spp. in both trials (Table 3). *F. oxysporum* and *Phytophthora* spp. levels were significantly higher in the untreated plots compared with FSD treatments ($P = 0.05$).

FSD1 treatments reduced *F. oxysporum* by 44.7% and 73.9% in trial I and trial II, respectively; FSD2 treatments provided similar control on *F. oxysporum* with reductions of 62.6% and 78.4%, respectively (Table 3). Similarly, FSD1 reduced *Phytophthora* spp. by 56.1% and 47.3% in trials I and II, respectively; FSD2 treated plots provided higher reductions of 70.2% and 48.9%, respectively (Table 3). However, there was no significant difference between FSD1 and FSD2 in controlling *F. oxysporum* and *Phytophthora* spp. ($P = 0.05$).

Table 1
Soil characteristics at the experimental sites.

Site	N/NH_4^+ (mg/kg)	N/NO_3^- (mg/kg)	Available P (mg/kg)	Available K (mg/kg)	Organic matter (g/kg)	pH (1:2.5)	Electrical conductivity (μs/cm)
Trial I, 2013	8.0	76.8	35.6	108.7	14.8	6.6	712.0
Trial II, 2014	7.2	59.7	51.0	68.8	10.7	5.5	388.0