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Nematicidal Potential of Selected Furfural Derivatives Against Meloidogyne incognita and Tylenchulus semipenetrans: Toward Sustainable Nematode Management.

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Abstract

Nematicides are used in controlling plant parasitic nematode for many years. The harmful effect of nematicides was threaten the environment so that there was a high need to find alternatives. Furfural derivatives are one of the promising alternatives to fill this need. In this study 6 furfural derivatives were Synthesised and applied against *Meloidogyne incognita* and *Tylenchulus semipenetran* . In vitro tests showed gradual mortality rates in the second stage juvenile (J2) of *M. incognita* and *T.semipenetran* when immersed in concentrations of furfural derivatives. These results indicated that furfural derivatives can affect juvenile viability of *M. incognita* and *T. semipenetran* . Furfural derivatives may therefore be one of the considerable potentials as an appropriate alternative for class I nematicides. Furfural derivatives were toxic to both tested nematode species. The toxic effect was more pronounced by increasing furfural concentration and exposure time (especially at 2h exposure). After 12 h, no viable J2 were detected at high concentrations (1.5%).

Keywords: Furfural, Furfural derivatives, Control, Eco-friendly, *Meloidogyne* spp., *Tylenchulus semipenetran*,

1. Introduction

Plant parasitic nematodes (PPNs) are considered one of the most significant pathogens for various crops worldwide, including vegetables, fruits, grains, and ornamental plants. They damage crops directly by feeding on plant roots and indirectly by cooperate with other soil microorganisms, causing complex diseases that increase the plant's susceptibility to secondary infections by fungi and bacteria. Moreover, they play a role as vectors for several plant viruses **[1]**

Root-knot nematodes (RKNs), specifically *Meloidogyne* spp., are regarded as the most destructive and well-known group of plant parasitic nematodes globally. These are obligate, endoparasitic nematodes that infest the roots of crops. *Meloidogyne* spp. cause significant losses in numerous economically important crops worldwide and have a broad host range, including over 5,500 plant species **[2]**. They are responsible for approximately 5% of global crop losses. When *Meloidogyne* spp. attack plant roots, root galls are formed due to their parasitic feeding behavior. [3]

The citrus nematode, *Tylenchulus semipenetrans*, which is the main cause of 'slow decline' in citrus, is one of the most damaging nematode pests of citrus crops, leading to severe crop losses globally. Management of the citrus nematode is challenging due to its wide host range and its ability to adapt to various climatic conditions **[4]**

Nematicides have been used for controlling plant parasitic nematodes for many years. However, the harmful effects of these chemicals have raised concerns about environmental pollution. **[5]**

The use of nematicides threatens ecosystems by contaminating the soil, air, and water, and damaging the beneficial microflora and microfauna. Additionally, they can interfere with the uptake of essential nutrients by plants and adversely affect other organisms, including bees and humans. **[6]**

Nematicides can alter the biochemical and physiological behavior of soil microorganisms, causing disruptions in soil ecosystems and potentially entering the food chain, thereby posing risks to human health. Therefore, there is an urgent need to explore eco-friendly alternatives to nematicides **([7]**

Furfural (2-furancarboxaldehyde) is a naturally occurring organic compound produced from organic agricultural residues such as brans, cereal straw, and sugarcane bagasse **[8]**

The functional groups and molecular weight of furfural have been precisely identified using GC-MS spectroscopy. It has a molecular formula of $C_5H_4O_2$ and a molecular weight of 96.0. The IR spectrum shows a very strong absorption at 1714.46 cm^{-1}, corresponding to the conjugated carbonyl (C=O) functional group **[9]**

Furfural residues play an important role in improving soil properties, as they are rich in carbon (pH = 2) and contain valuable nutrients. These properties can enhance the pH (reducing alkalinity), bulk density, compactness, water holding capacity, and overall soil quality. Furfural is known to act as a fungicide, nematicide, and weed killer. It is a contact safety nematicide that can be used effectively in low concentrations, making it a safe and easy-to-apply alternative **[10]**

The aim of this study is to synthesize furfural derivatives and evaluate their effects on the juvenile stages (J_2) of *Meloidogyne* spp. and *Tylenchulus semipenetrans*.

2. Materials and methods

Synthesis of furfural derivatives:

Furfural derivatives were synthesized through a one-step condensation reaction using furfural as the

starting material. All synthesized compounds belong to the class of Schiff bases. These compounds were selected due to their straightforward synthesis, cost-effectiveness, and rapid reaction kinetics. The Schiff base formation occurred readily at room temperature, with some reactions completing within minutes under ambient (cold) conditions, without the need for heating or complex catalysts, making the procedure both energy-efficient and environmentally friendly. **[11]**

Structure investigation of the synthesized compounds:

The chemical structures of the synthesized compounds were confirmed using spectroscopic techniques, including Infrared (IR) Spectroscopy and Nuclear Magnetic Resonance (NMR) Spectroscopy. [12]). IR spectroscopy was employed to identify characteristic functional groups, particularly the imine (C=N) stretching vibrations indicative of Schiff base formation. Proton (^1H) and Carbon (^13C) NMR spectra were recorded to elucidate the structural framework and confirm the expected chemical shifts corresponding to the aromatic and imine protons, supporting the successful synthesis of the target compounds**[13]**

Reaction procedure:

Schiff bases were synthesized via a condensation reaction between furfural and various aromatic amine or active methylene compounds. Equimolar amounts (1:1 molar ratio) of furfural and the selected amine derivative were dissolved in ethanol and stirred at ambient temperature. The reaction progress was monitored by Thin Layer Chromatography (TLC). Upon completion, the resulting product was isolated by filtration, dried, and purified through recrystallization from ethanol. The general reaction scheme is depicted in Figure 1**. [14]**

Nematode stock culture

Meloidogyne incognita

A stock culture of *Meloidogyne incognita* was established from a single, well-identified fresh egg mass originally isolated from *Coleus blumei* roots infected with *M. incognita*. The infected plants were maintained under controlled conditions in the greenhouse of the Faculty of Agriculture, Benha University, Egypt. The pure culture of M. incognita was incubated under laboratory condition (25 ± 3 C,60± 10% RH) and used in all assays.

The nematode culture was propagated and maintained on *Coleus* plants to ensure purity and uniformity, and was used as the inoculum source for all experimental assays.**[8]**

Tylenchulus semipenetrans

The stock culture of *Tylenchulus semipenetrans* was similarly established from a single, well-identified fresh egg mass collected from infected citrus roots in a field located at the Faculty of Agriculture, Benha University, Egypt. the roots from soil samples was gently washed free of soil and was cut into 2cm long pieces, placed in plastic dishes with distilled water and incubated under laboratory condition 25 ± 3 C,60± 10% RH) and blended at 3000rpm for 3 min to extract eggs from roots . The nematode was subsequently propagated on citrus plants in greenhouse conditions to maintain a pure and viable culture. This culture served as the source of nematodes for all experimental procedures. **[15]**

Micro-well assays

Second-stage juveniles (J_2) of *Meloidogyne incognita* were prepared for the assays following the method described by **[16].** Fresh egg masses were carefully collected from infected plant roots and initially suspended in tap water. The suspension was then rinsed three times with sterile deionized water (DIW) to ensure cleanliness. To obtain J_2, the eggs were placed on a Baermann funnel setup and incubated at room temperature to allow hatching. After approximately 48 hours, hatched J_2 were collected using 25 µm sieves and immediately used for the micro-well assay experiments.

Bioassay setup

Bioassays were conducted using 24-well flat-bottom plates, following a procedure similar to that described by **[17].** Previously hatched second-stage juveniles (J_2) of *Meloidogyne incognita* were introduced into individual wells for treatment.

Preparation of Test Solutions and Compounds

Each test solution was prepared by dissolving 0.1 g of the active compound in 2 mL of dimethyl sulfoxide (DMSO), and the volume was brought up to 1000 mL using sterile deionized water (DIW). This stock solution was considered the 100% concentration. The compounds tested included the following furfural-derived Schiff bases:

1. 2-(Furan-2ylmethylene)malononitrile
2. 1-(Furan-2-ylmethylene)-2-phenylhydrazine
3. 1-(4-Bromophenyl)-2-(furan-2-ylmethylene)hydrazine
4. 2-(Furan-2-ylmethylene)hydrazine-1-carbothioamide
5. 4-(2-(Furan-2-ylmethylene)hydrazine)benzoic acid
6. 2-(2-(Furan-2-ylmethylene)hydrazine)phenol

These solutions were used to evaluate the nematicidal activity of the synthesized compounds under controlled laboratory conditions.

Application of treatments and experimental design

Various concentrations of each furfural-derived compound were tested to evaluate their nematicide activity. For treatment application, each well received 0.5 mL of a double-concentrated furfural derivative solution (or DMSO as a control) and 0.5 mL of a *Meloidogyne incognita* suspension containing approximately 300 freshly hatched second-stage juveniles (J_2). This resulted in a final treatment volume of 1 mL per well and yielded the desired concentrations of 0%, 0.375%, 0.75%, and 1.5% for each compound**. .[8]**

The 24-well plates were incubated at 25 °C under controlled conditions. Four wells were used for each treatment concentration per trial, and the entire experiment was independently repeated twice, resulting in a total sample size of $n = 8$ for each treatment group. **[17]**

Nematode viability was assessed at multiple time intervals: 1 minute, 30 minutes, 1 hour, 2 hours, 12 hours, 18 hours, 24 hours, and 48 hours after exposure. At each time point, the total number of J_2 and the number of active (motile) versus inactive (non-motile) individuals were recorded to determine mortality and behavioral response to treatment. After nematodes have been extracted from soil or plant , was counted and identified to genus level using a counting slide for species identification with a dissecting microscope. **[18]**

Confirmation of Juvenile Mortality

At the end of the experiment, to confirm juvenile mortality, one drop of freshly prepared 1.0 mol L^{-1} sodium hydroxide (NaOH) solution was added to each well, following the method described **[19]**. Immobile juveniles were recounted within two minutes of NaOH application. Juveniles that remained unresponsive were considered dead, ensuring accurate mortality assessment and minimizing the possibility of false negatives due to temporary immobilization.

Statistical analysis:

Statistical analyses were performed using SPSS software, version 12.0.1 (SPSS Inc., Chicago, IL, USA). Data were expressed as means ± standard error (SE). Differences between treatment groups were evaluated using Tukey's Honestly Significant Difference (HSD) test to determine statistically significant variations among means. A *p*-value of less than 0.05 was considered indicative of statistical significance.

3. Results

Synthesized furfural derivatives

Six organic compounds were synthesized from furfural and are expected to exhibit notable biological activity. Structural confirmation was performed using Fourier Transform Infrared Spectroscopy (FT-IR) and Proton Nuclear Magnetic Resonance (^1H NMR) spectroscopy. The analytical data for two representative compounds are presented below:

2-(furan-2-ylmethylene)malononitrile (FM): FT-IR (KBr pellet) at 3123,3041 cm^{-1} ($\nu_{=CH}$), 2224 ($\nu_{C\equiv N}$) and 1603,1569 cm^{-1} ($\nu_{C=C}$).[Figure 2], ^{1}H NMR-400 MHz, d ppm: ٦.٩٠ (١H, [=CH-O]), 7.44(1H, [$(CN)_2$-C=CH], 8.28 (2H, [=CH-CH=]). [Figure 3]

1-(furan-2-ylmethylene)-2-phenylhydrazine (FZ): FT-IR (KBr pellet) at = 3318 cm^{-1} (ν_{NH}), 3148, 3114 cm^{-1} ($\nu_{=CH}$) and 1598 ($\nu_{C=N}$). [Figure 4], ^{1}H NMR-400 MHz, d ppm: ٦.٩٠(١H, [=CH-O]), 7.12, 7.14 (5H, [Ph], 7.18(NH-C=CH], 7.71, 7.88 (2H, [=CH-CH=]), 10.26 (1H, [Ph-NH-]). [Figure 5]

1-(4-bromophenyl)-2-(furan-2-ylmethylene)hydrazine (FB): FT-IR (KBr pellet) at = 3344 cm^{-1} (ν_{NH}), 3141, 3004 cm^{-1} ($\nu_{=CH}$), 1633 cm^{-1} ($\nu_{C=N}$) and 1588 cm^{-1} ($\nu_{C=C}$). [Figure 6], 1H NMR-400 MHz, d ppm: ٦.49(١H, [=CH-O]), 6.51-7.14 (5H, [Ph]), 7.18(NH-C=CH], 7.47 (2H, [=CH-CH=]), 7.55 (1H, [Ph-NH-]). [Figure 7]

2-(furan-2-ylmethylene)hydrazine-1-carbothioamide (FC): FT-IR (KBr pellet) at = 3410 cm^{-1} (ν_{NH}), 3134, 3015 cm^{-1} ($\nu_{=CH}$), 1608 cm^{-1} ($\nu_{C=N}$), 1581 cm^{-1} ($\nu_{C=C}$). [Figure 8], ^{1}H NMR-400 MHz, d ppm: ٦.61(١H, [=CH-O]), 7.96 (1H, NH-C=CH]), 7.61, 7.80 (2H, [-NH_2]), 7.96, 8.20 (2H, [=CH-CH=]), 11.41 (1H, [-NH-]). [Figure 9]

4-(2-(furan-2-ylmethylene)hydrazinyl)benzoic acid (FO): FT-IR (KBr pellet) at = 3347 cm^{-1} (ν_{NH}), 3500-2250 cm^{-1} (broad band of $\nu_{OH\ carboxylic}$), 1667 cm^{-1} ($\nu_{C=O}$), 1598 cm^{-1} ($\nu_{C=C}$). [Figure 10], ^{1}H NMR-400 MHz, d ppm: ٦.78 (١H, [=CH-O]), 6.78, 7.37 (5H, [Ph]), 6.94 (1H, [NH-C=CH], 6.91, 7.01 (2H, [=CH-CH=]), 8.38 (1H, [Ph-NH-]), 12.18 (1H, -COOH])> [Figure 11]

2-(2-(furan-2-ylmethylene)hydrazinyl)phenol (FP): FT-IR (KBr pellet) at = 3335 cm^{-1} (ν_{NH}), 3500-2250 cm^{-1} (broad band of ν_{OH}), 1633 cm^{-1} ($\nu_{C=N}$), 1633 cm^{-1} ($\nu_{C=N}$) and 1574 cm^{-1} ($\nu_{C=C}$). [Figure 12], ^{1}H NMR-400 MHz, d ppm: ٦.78, 6.91, 6.94, 7.01, 6.78, 7.37 and ٩.٥٠ [Figure 13]

Microwell bioassays

J2 Mortality of *Meloidogyne incognita* in Response to Furfural Derivatives

Second-stage juveniles (J_2) of *Meloidogyne incognita* were exposed to various concentrations (1.5%, 0.75%, and 0.375%) of the synthesized furfural derivatives over different time intervals (0, 0.5, 1, 2, 12, 18, and 24 hours).

The results demonstrated a concentration- and time-dependent increase in juvenile mortality for all tested compounds.

At the highest concentration (1.5%), all furfural derivatives induced 100% mortality within 2 hours, confirming their strong and rapid nematicidal activity. At the intermediate concentration (0.75%), differences in efficacy and speed of action were observed among the compounds. Notably, FM and FC exhibited faster and more potent activity compared to FP and FO, which required longer exposure times to achieve similar mortality levels.

At the lowest concentration tested (0.375%), mortality rates increased gradually over time, with full mortality not achieved within the 24-hour exposure

period for most compounds. This indicates that both the dose and duration of exposure are critical determinants of nematicidal efficacy.

Control treatments with sterile deionized water (DIW) and dimethyl sulfoxide (DMSO) showed no significant effect on J_2 mortality, confirming that the observed nematicidal activity was attributable solely to the furfural-derived compounds **(Table 1).**

J_2 Mortality of *T. semipenetrans* in response to furfural derivatives

The mortality rates of second-stage juveniles (J_2) of *Tylenchulus semipenetrans* were evaluated following exposure to various concentrations (1.5%, 0.75%, and 0.375%) of furfural derivatives over different time intervals (0, 0.5, 1, 2, 12, 18, and 24 hours). The results demonstrate a significant nematicidal effect of these compounds, with mortality increasing over time.

At the highest concentration (1.5%), all tested compounds achieved 100% mortality within 2 hours, indicating the rapid and potent activity of these derivatives in controlling *T. semipenetrans*. At the intermediate concentration (0.75%), the onset of action varied among compounds; for instance, FM and FC induced faster and more effective mortality compared to FP and FO.

At the lowest concentration (0.375%), the time required to reach comparable mortality levels was significantly longer, suggesting a clear dose- and time-dependent relationship.

Control treatments using sterile distilled water (DIW) and dimethyl sulfoxide (DMSO) showed no significant effect on nematode mortality, confirming that the observed lethality was attributable solely to the furfural derivatives **(Table 2).**

The results obtained indicate that all furfural derivatives tested in this study exhibit a strong ability to reduce the number of nematode larvae under laboratory conditions. Consequently, the lowest concentration tested (0.375%) was selected to compare key parameters and identify the most effective compound for potential future applications, as presented in **(Table 3).**

Among the derivatives, FC demonstrated the highest nematicidal activity, achieving nearly 50% mortality of J_2 larvae from both nematode species within just 30 minutes of exposure **(Table 3).** This highlights FC as a particularly promising candidate for further investigation.

Furfural derivatives exhibited significant toxicity against second-stage juveniles (J_2) of *Meloidogyne incognita* and *Tylenchulus semipenetrans*. Regression analysis indicated a marked increase in J_2 mortality even at low concentrations, with toxicity intensifying as both concentration and exposure time increased—particularly during the first 12 hours.

By the 12-hour mark, no viable J_2 were detected in treated groups, while the water control consistently showed 0% mortality throughout the experiment, confirming the absence of natural mortality and reinforcing the effectiveness of the compounds **(Figures 14 and 15)**

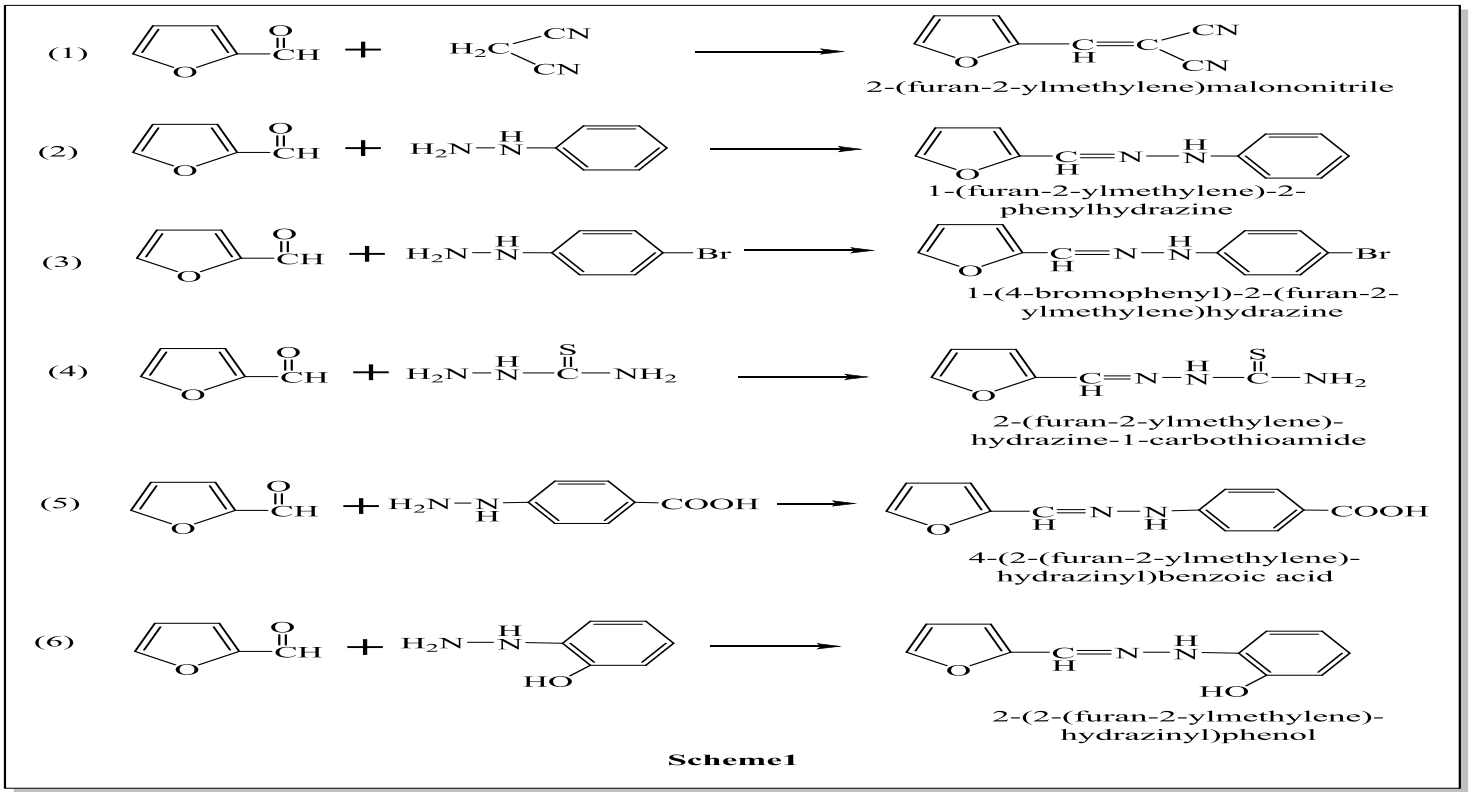

Fig. 1: Synthesis reactions of furfural derivatives

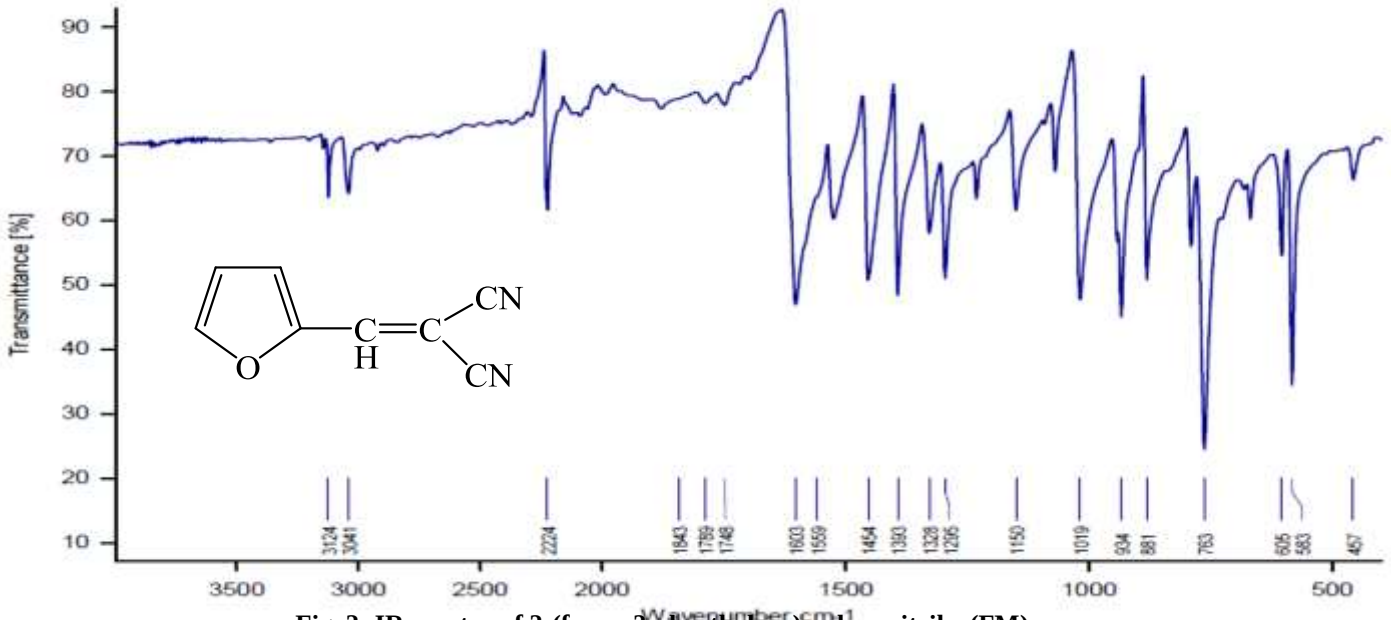

Fig. 2: IR spectra of 2-(furan-2-ylmethylene)malononitrile (FM)

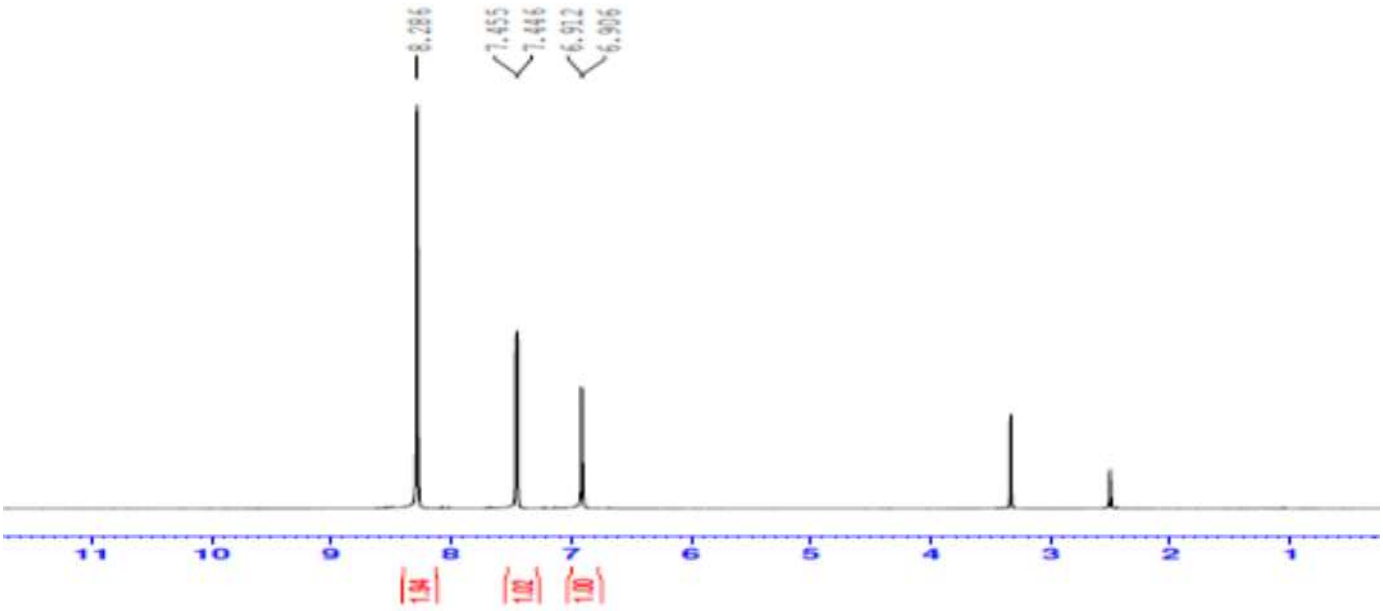

Fig. 3: ^{1}H NMR spectra of 2-(furan-2-ylmethylene)malononitrile (FM)

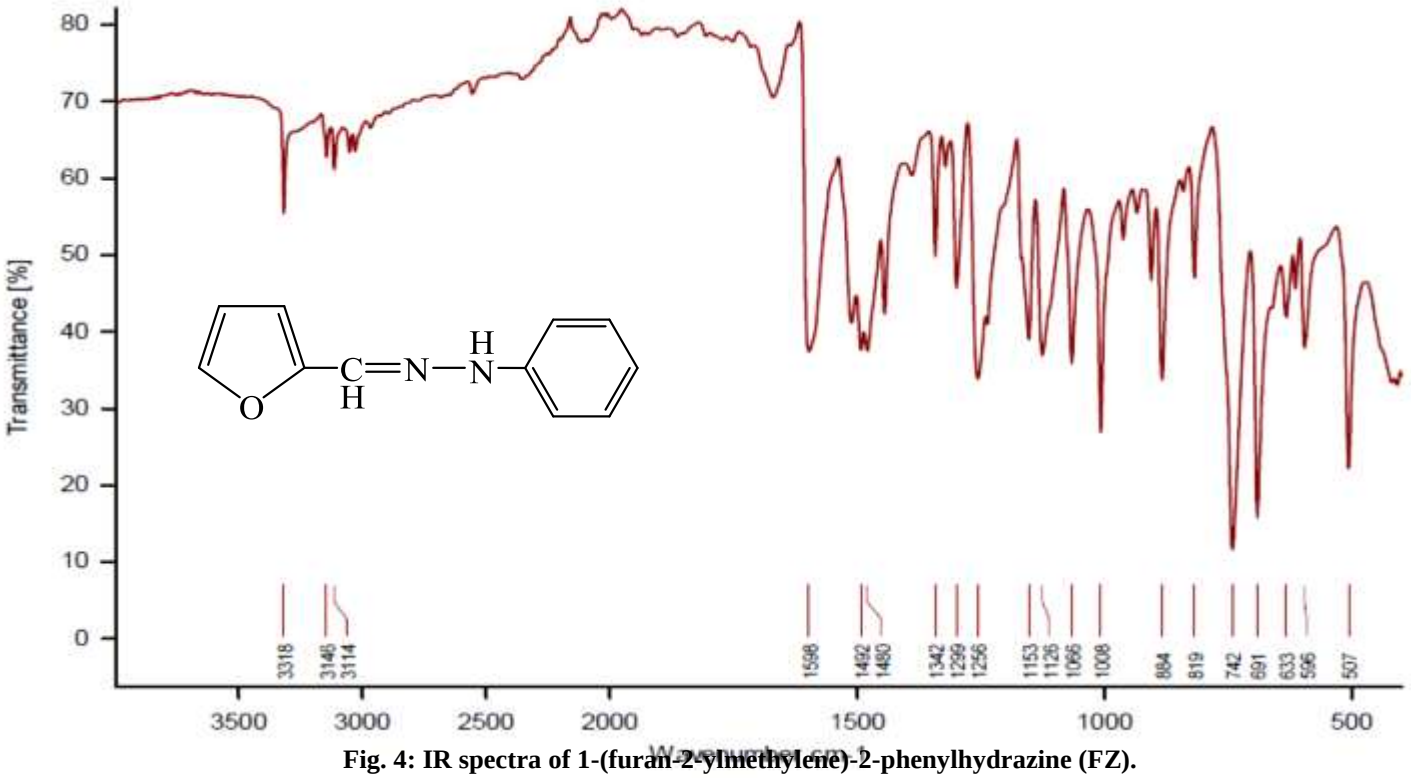

Fig. 4: IR spectra of 1-(furan-2-ylmethylene)-2-phenylhydrazine (FZ).

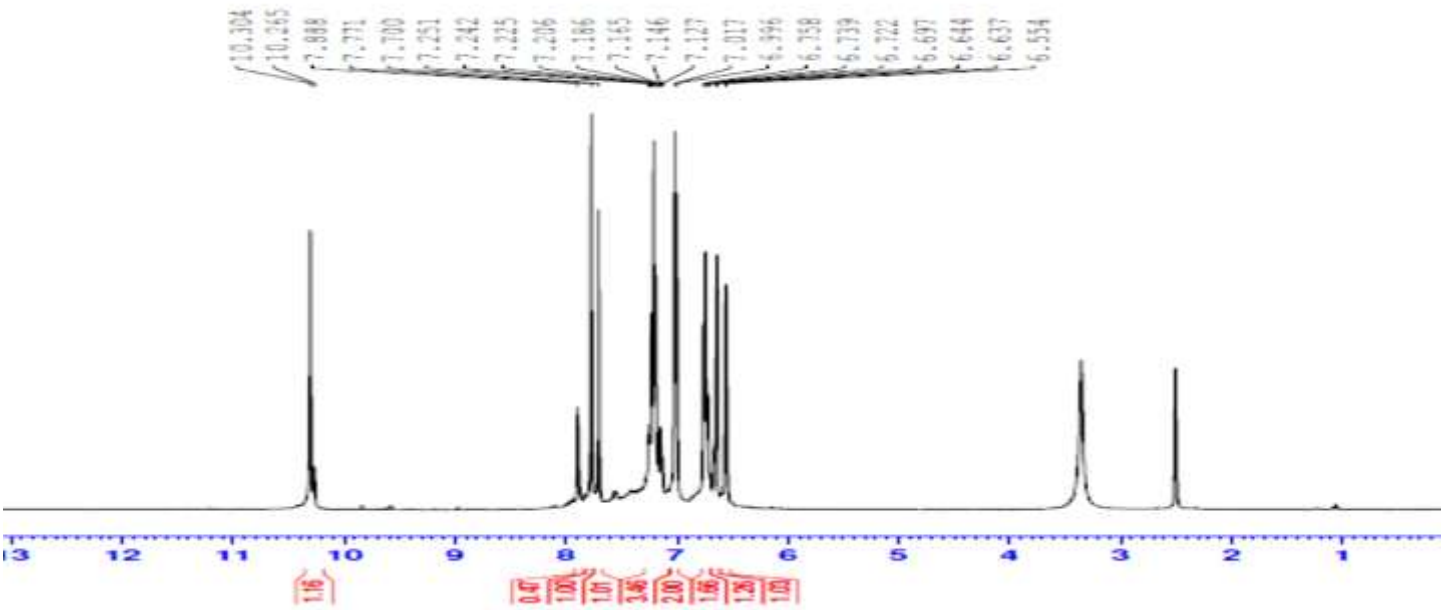

Fig. 5: ^{1}H NMR spectra of 1-(furan-2-ylmethylene)-2-phenylhydrazine (FZ)

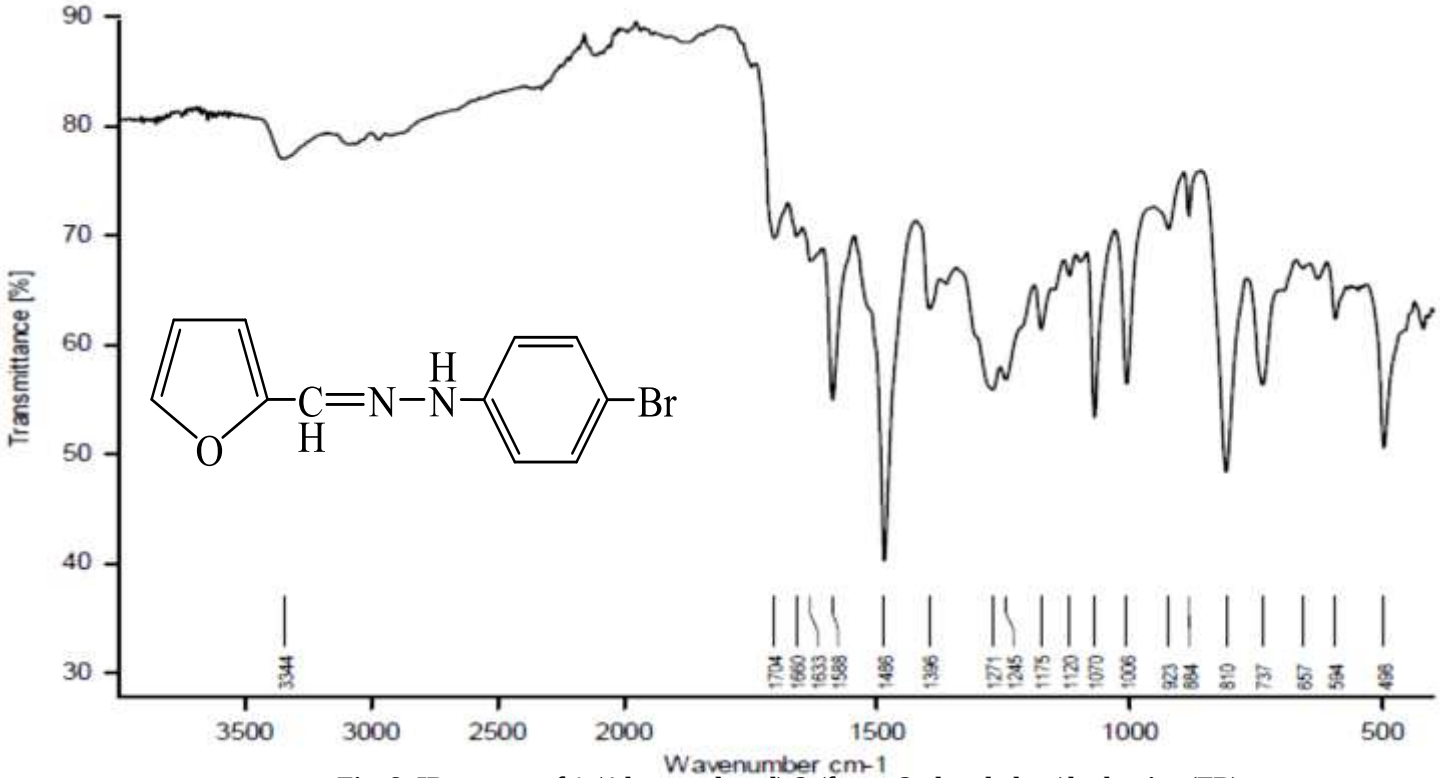

Fig. 6: IR spectra of 1-(4-bromophenyl)-2-(furan-2-ylmethylene)hydrazine (FB).

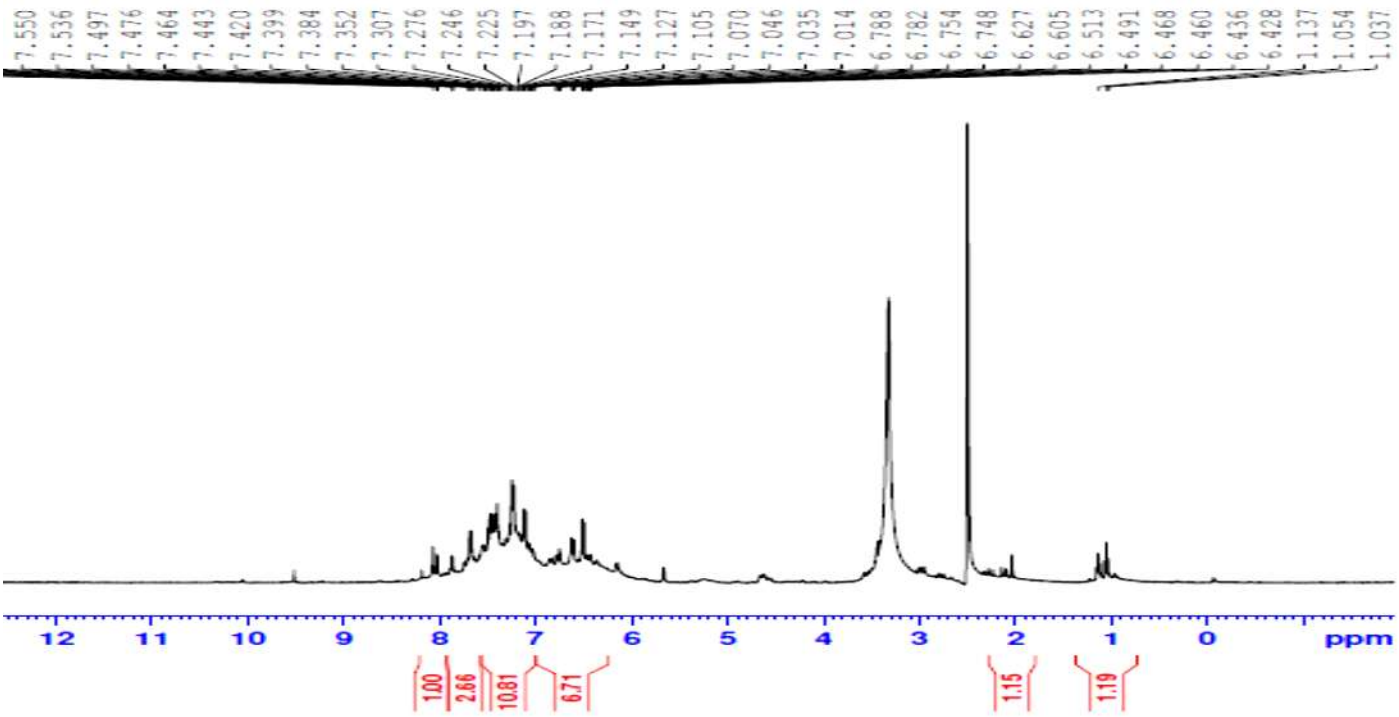

Fig. 7: ^{1}H NMR spectra of 1-(4-bromophenyl)-2-(furan-2-ylmethylene)hydrazine (FB).

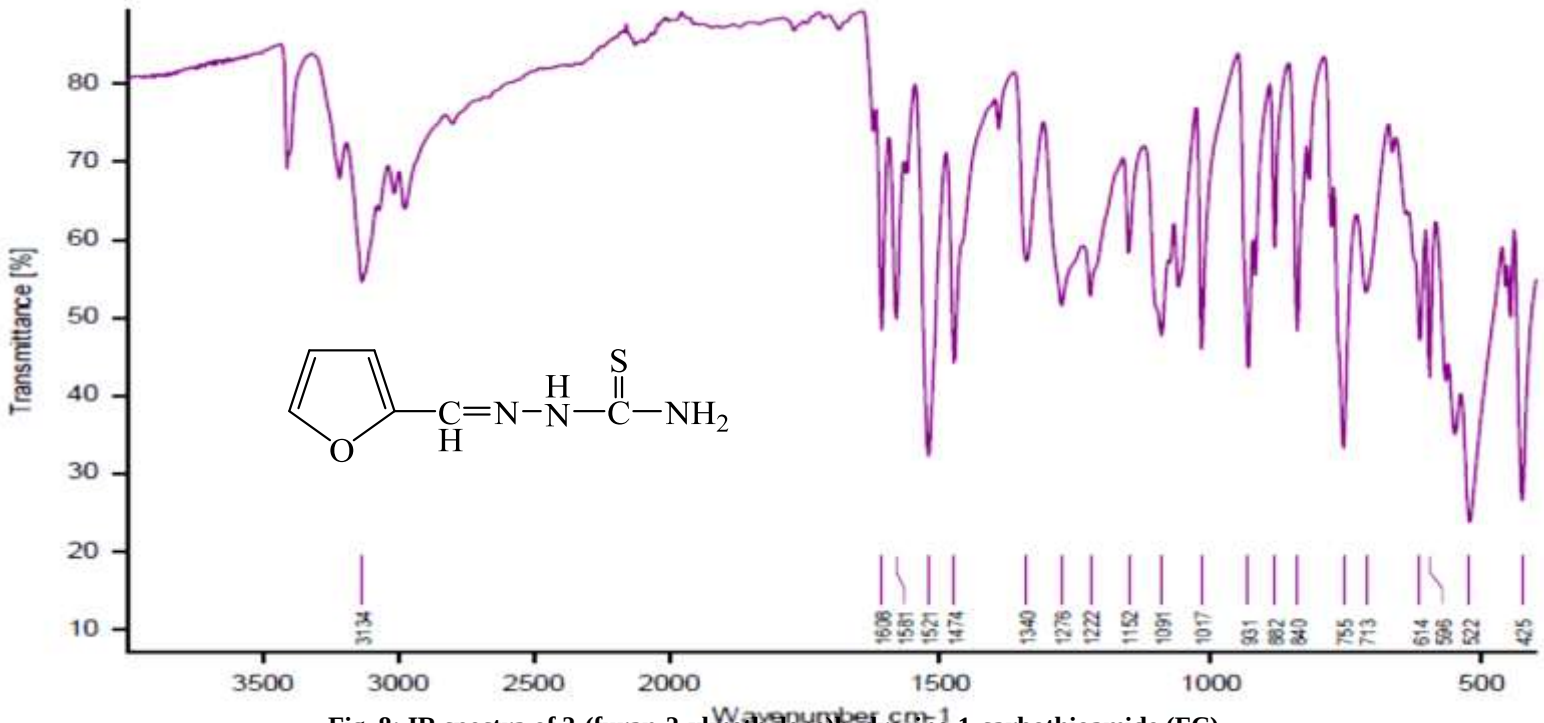

Fig. 8: IR spectra of 2-(furan-2-ylmethylene)hydrazine-1-carbothioamide (FC).

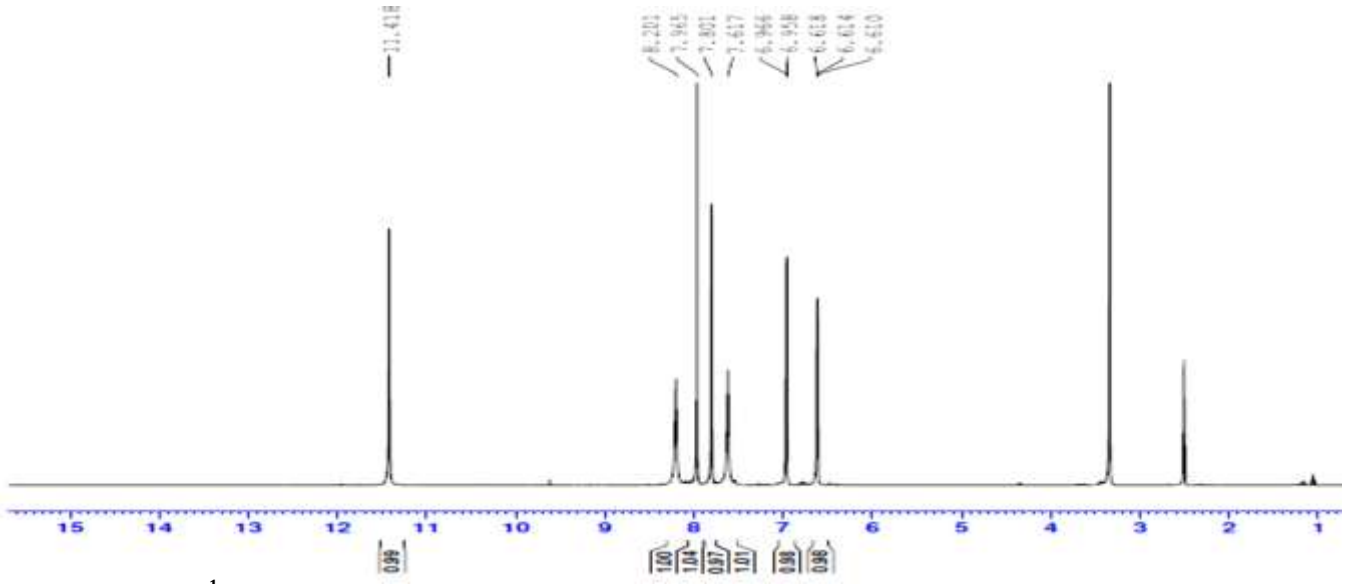

Fig. 9: ^{1}H NMR spectra of 2-(furan-2-ylmethylene)hydrazine-1-carbothioamide (FC).

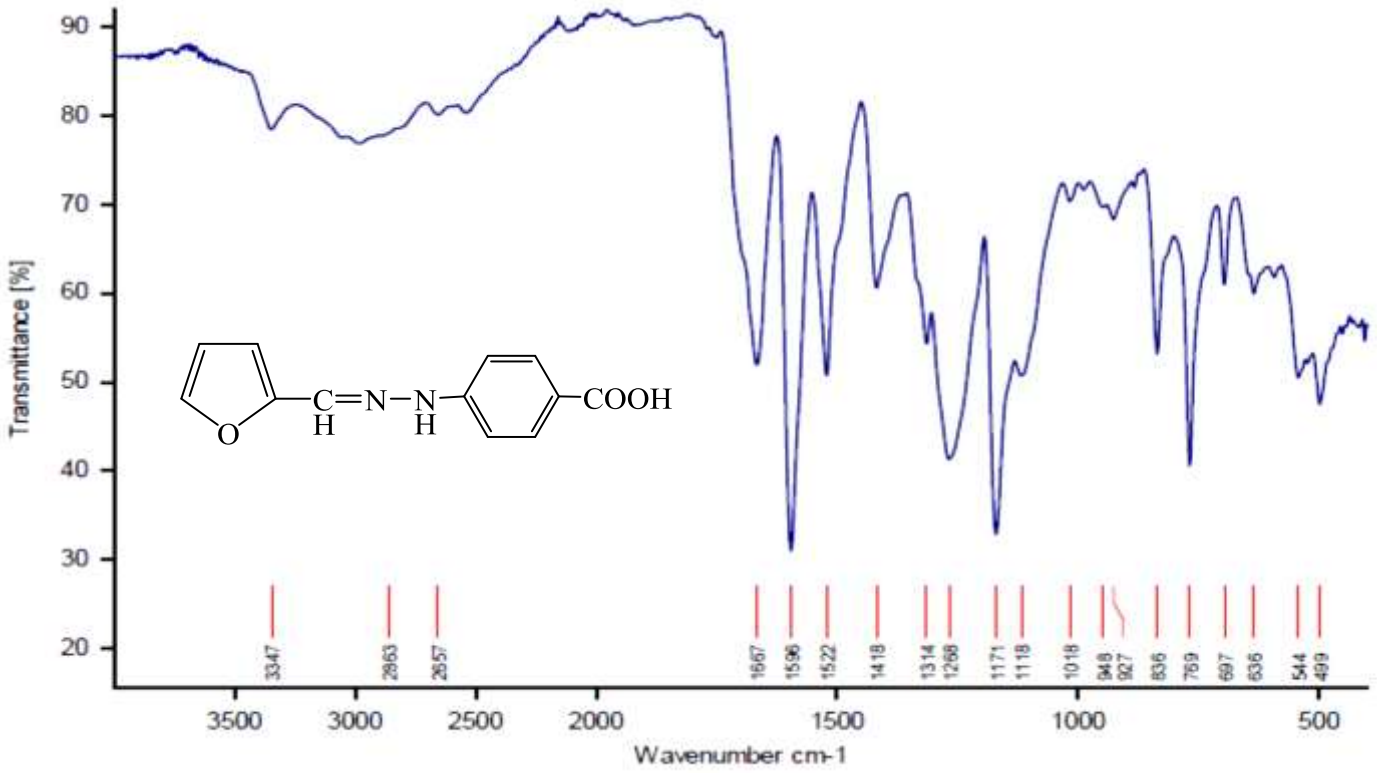

Fig. 10: IR spectra of 4-(2-(furan-2-ylmethylene)hydrazinyl)benzoic acid (FO).

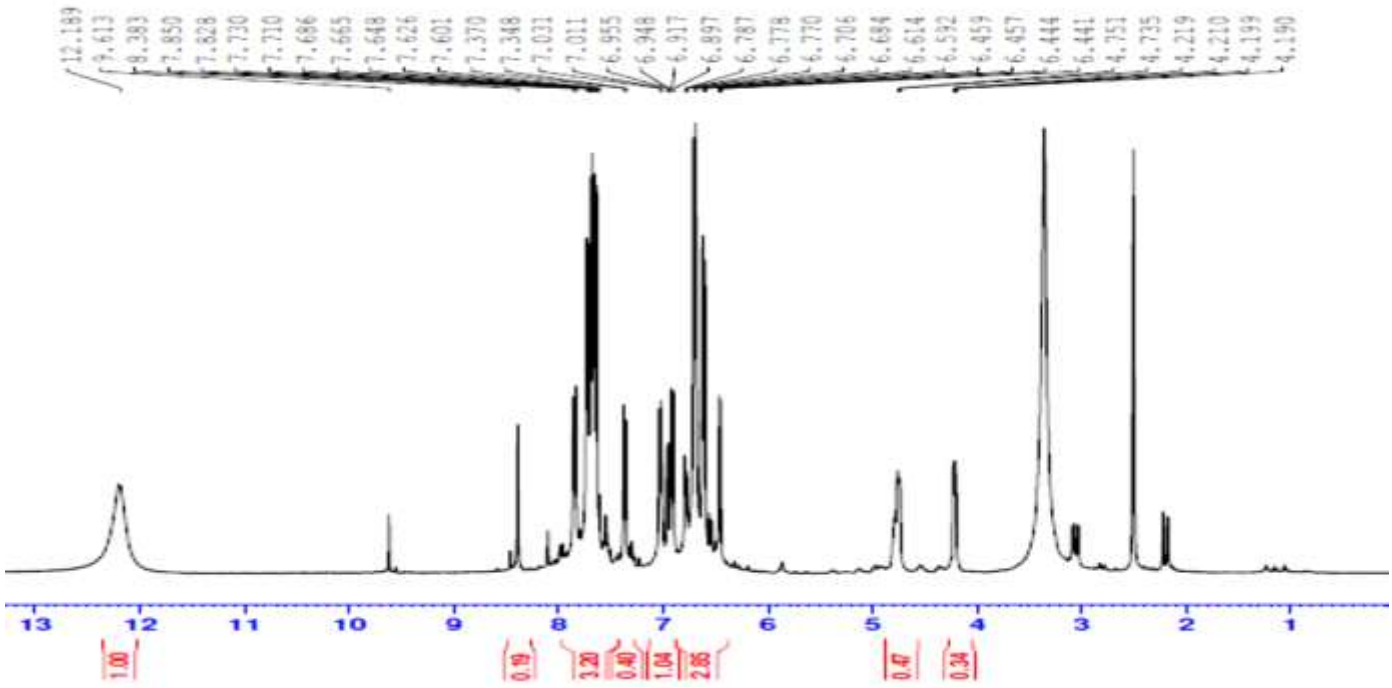

Fig. 11: ^{1}H NMR spectra of 4-(2-(furan-2-ylmethylene)hydrazinyl)benzoic acid (FO).

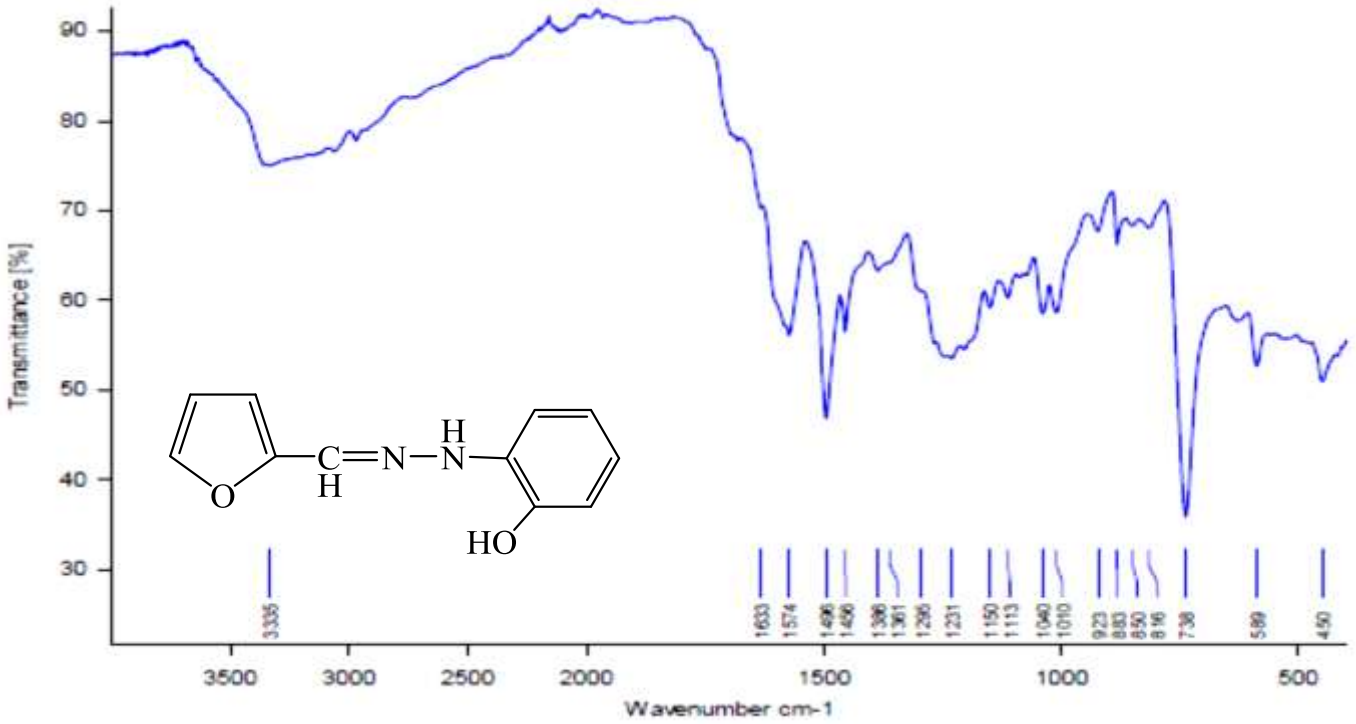

Fig. 12: IR spectra of 2-(2-(furan-2-ylmethylene)hydrazinyl)phenol (FP).

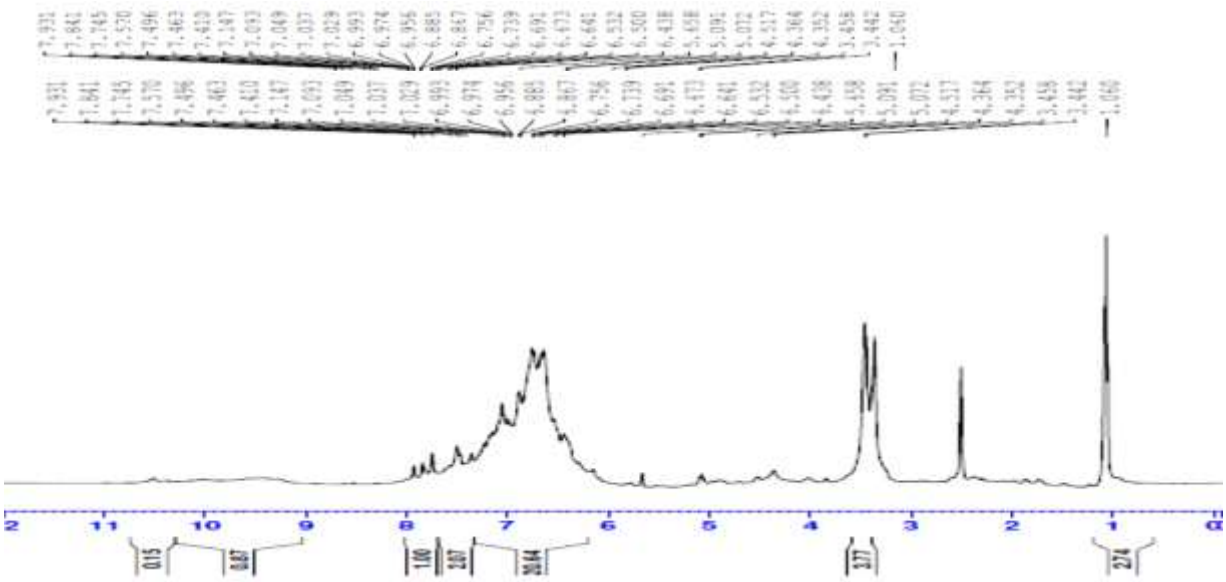

Fig. 13: ^{1}H NMR spectra of 2-(2-(furan-2-ylmethylene)hydrazinyl)phenol (FP).

Table (1): Impact of on furfural derivatives on Juveniles mortality% of *Meloidogyne incognita* (mean±SE).

Treat-ment	Conc. (%)	Period (hrs.) 0	0.5	1	2	12	18	24	Mean
FM	1.50	0±0^{aC}	75.67 ±5.23^{aB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	82.24 ±4.72^{a}
	0. 75	0±0^{aD}	49.46 ±3.48^{cC}	84.25 ±5.00^{bB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	76.24 ±4.86^{b}
	0. 375	0±0^{aD}	20.17 ±2.17^{eC}	49.96 ±6.43^{gB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	67.16 ±5.50^{d}
FZ	1.50	0±0^{aD}	49.92 ±2.77^{cC}	80.92 ±7.55^{cB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	75.83 ±4.9^{b}
	0.75	0±0^{aD}	33.96 ±2.68^{dC}	75.13 ±6.10^{dB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	72.73 ±5.12^{c}
	0.375	0±0^{aD}	20.00 ±1.42^{eC}	50.04 ±6.07^{gB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	67.15 ±5.49^{d}
FB	1.50	0±0^{aD}	0±0^{fD}	40.13 ±3.91^{hC}	50.21 ±4.20^{bB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	55.76 ±5.72^{e}
	0.75	0±0^{aD}	0±0^{fD}	19.87 ±2.46^{iC}	30.00 ±1.68^{dB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	49.98 ±6.00^{gh}
	0.375	0±0^{aD}	0±0^{fD}	10.12 ±1.22^{lC}	25.04 ±1.21^{eB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	47.88 ±6.18^{h}
FC	1.50	0±0^{aC}	74.84 ±3.23^{aB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	82.12 ±4.69^{a}
	0.75	0±0^{aD}	59.84 ±4.28^{bC}	71.42 ±2.25^{eB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	75.89 ±4.71^{b}
	0.375	0±0^{a}R	49.92 ±5.16^{cC}	60.21 ±5.09^{fB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	72.88 ±4.92^{c}
FO	1.50	0±0^{aD}	0±0^{fD}	20.00 ±2.78^{iC}	50.29 ±4.61^{bB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	52.90 ±5.93^{f}
	0.75	0±0^{aD}	0±0^{fD}	15.04 ±1.46^{kC}	30.00 ±1.87^{dB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	49.29 ±6.06^{gh}
	0.375	0±0^{aD}	0±0^{fD}	10.04 ±0.98^{kC}	25.50 ±1.84^{eB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	47.93 ±6.18^{h}
FP	1.50	0±0^{aD}	0±0^{fD}	20.21 ±2.70^{iC}	50.17 ±4.97^{bB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	52.91 ±5.93^{f}
	0.75	0±0^{aD}	0±0^{fD}	17.96 ±2.04^{jC}	35.92 ±1.61^{cB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	50.55 ±5.98^{g}

	0.375	0±0^{aD}	0±0^{fD}	10.00 ±1.13^{lC}	25.08 ±1.71^{eB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	47.87 ±6.18^{h}
Sterile deionized water (DIW)		0±0^{aA}	0±0^{fA}	0±0^{mA}	0±0^{fA}	0±0^{bA}	0±0^{bA}	0±0^{bA}	0±0^{i}
DMSO		0±0^{aA}	0±0^{fA}	0±0^{mA}	0±0^{fA}	0±0^{bA}	0±0^{bA}	0±0^{bA}	0±0^{i}
Mean		0±0^{E}	21.69 ±2.22^{D}	41.76 ±2.73^{C}	61.11 ±2.99^{B}	90.00 ±2.38^{A}	90.00 ±2.38^{A}	90.00 ±2.38^{A}	

a, b & c: There is no significant difference (P>0.05) between any two means, within the same column have the same superscript letter.

A, B & C: There is no significant difference (P>0.05) between any two means, within the same row have the same superscript letter.

١.٩٢ LSDC

١.١٤ LSDP

٥.٠٩ LSDC

Table (2): Impact of furfural derivatives on Juveniles mortality % of *Tylenchulus semipenetrans* (mean±SE).

Treat-ment	Conc. (%)	Period (hrs) 0	0.5	1	2	12	18	24	Mean
FM	1.50	0±0^{aE}	64.42 ±3.95^{aD}	88.44 ±4.34^{aC}	90.20 ±4.36^{bB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	76.07 ±5.13^{a}
	0.075	0±0^{aE}	45.75 ±5.16^{eD}	61.67 ±3.26^{fC}	71.60 ±1.86^{eB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	68.65 ±5.25^{d}
	0.0375	0±0^{aE}	20.00 ±1.98^{gD}	43.07 ±1.59^{iC}	62.60 ±3.71^{gB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	61.77 ±5.78^{e}
FZ	1.50	0±0^{aE}	57.13 ±5.54^{bD}	85.06 ±2.42^{bC}	95.60 ±1.81^{aB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	76.36 ±5.48^{a}
	0.75	0±0^{aE}	49.87 ±5.39^{dD}	72.13 ±2.88^{eC}	90.80 ±2.38^{bB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	72.27 ±5.26^{c}
	0.375	0±0^{aE}	22.17 ±0.99^{fD}	48.07 ±2.84^{hC}	65.40 ±6.03^{fB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	62.89 ±5.72^{e}
FB	1.50	0±0^{aE}	10.21 ±0.84^{iD}	29.96 ±1.52^{kC}	47.13 ±1.81^{iB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	55.79 ±5.85^{g}
	0.75	0±0^{aE}	5.29 ±0.89^{jD}	19.92 ±2.08^{lC}	30.04 ±1.85^{lB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	50.75 ±5.89^{h}
	0.375	0±0^{aE}	0±0^{kD}	15.13 ±1.60^{mC}	19.71 ±1.16^{mB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	47.83 ±6.16^{i}
FC	1.50	0±0^{aE}	53.50 ±6.33^{cD}	81.47 ±4.97^{cC}	91.33 ±2.73^{bB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	75.19 ±5.55^{a}
	0.75	0±0^{aE}	49.47 ±4.94^{dD}	77.40 ±3.40^{dC}	79.00 ±5.68^{cB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	72.27 ±5.50^{b}
	0.375	0±0^{aE}	44.00 ±4.19^{eD}	55.53 ±2.50^{gC}	73.53 ±2.82^{dB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	67.95 ±5.28^{d}
FO	1.50	0±0^{aE}	20.00 ±1.51^{gD}	30.08 ±1.46^{kC}	54.40 ±3.55^{hB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	57.97 ±5.64^{f}
	0.75	0±0^{aE}	15.08 ±2.07^{hD}	19.04 ±1.56^{lC}	29.96 ±1.60^{kB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	52.01 ±5.72^{h}
	0.375	0±0^{aE}	0±0^{kD}	4.83 ±0.56^{nC}	25.42 ±2.05^{lB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	47.18 ±6.27^{i}
FP	1.50	0±0^{aE}	10.00 ±0.79^{iD}	35.43 ±1.21^{jC}	46.53 ±3.86^{iB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	56.94 ±5.90^{fg}
	0.75	0±0^{aE}	5.04 ±0.58^{jD}	18.46 ±1.35^{lC}	36.00 ±2.22^{jB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	51.36 ±5.87^{h}
	0.375	0±0^{aE}	0±0^{kD}	14.08 ±1.24^{mC}	24.96 ±1.62^{lB}	100 ±0.00^{aA}	100 ±0.00^{aA}	100 ±0.00^{aA}	48.43 ±6.12^{i}
Sterile deionized water (DIW)		0±0^{aA}	0±0^{kA}	0±0^{oA}	0±0^{nA}	0±0^{bA}	0±0^{bA}	0±0^{bA}	0±0^{j}
DMSO		0±0^{aA}	0±0^{kA}	0±0^{oA}	0±0^{nA}	0±0^{bA}	0±0^{bA}	0±0^{bA}	0±0j
Mean		0±0^{E}	21.61 ±1.85^{D}	34.35 ±2.46^{C}	46.60 ±2.72^{B}	90.00 ±2.38^{A}	90.00 ±2.38^{A}	90.00 ±2.38^{A}	

a, b & c: There is no significant difference (P>0.05) between any two means, within the same column have the same superscript letter.

A, B & C: There is no significant difference (P>0.05) between any two means, within the same row have the same superscript letter.

LSDC 1.49

LSDP 0.88

LSDCP 3.93

Table (3): Impact of furfural derivatives at concentration 0.375% for all treatment on Juveniles mortality% of *Meloidogyne incognita and Tylenchulus semipenetran*s (mean±SE).

Gene.	Treatment	Time (hrs.) 0	0.5	1	2	12	18	24	Mean
Meloidogyne incognita	FM	0±0^{a} D	20.17±2.17^{b} C	49.96±6.43^{c} B	100±0^{aA}	100±0^{a} A	100±0^{a} A	100±0^{a} A	67.16±5.50 b
	FZ	0±0^{a} D	20.00±1.42^{b} C	50.04±6.07^{b} B	100±0^{aA}	100±0^{a} A	100±0^{a} A	100±0^{a} A	67.15±5.49 b
	FB	0±0^{a} D	0±0^{cD}	10.12±1.22^{d} C	25.04±1.21^{b} B	100±0^{a} A	100±0^{a} A	100±0^{a} A	47.88±6.18 c
	FC	0±0^{a} D	49.92±5.16^{a} C	60.21±5.09^{a} B	100±0^{aA}	100±0^{a} A	100±0^{a} A	100±0^{a} A	72.88±4.92 a
	FO	0±0^{a} D	0±0^{cD}	10.04±0.98^{d} C	25.5±1.84^{bB}	100±0^{a} A	100±0^{a} A	100±0^{a} A	47.93±6.18 c
	FP	0±0^{a} D	0±0^{cD}	10.00±1.13^{d} C	25.08±1.71^{b} B	100±0^{a} A	100±0^{a} A	100±0^{a} A	47.87±6.18 c
	Mean	0±0^{E}	15.01±2.78^{D}	31.73±3.59^{C}	62.60±5.47^{B}	100±0^{A}	100±0^{A}	100±0^{A}	58.48±2.41
Tylenchulus semipenetrans	FM	0±0^{a} E	20.00±1.98^{c} D	43.07±1.59^{c} C	62.60±3.71^{c} B	100±0^{a} A	100±0^{a} A	100±0^{a} A	61.77±5.78 b
	FZ	0±0^{a} E	22.17±0.99^{b} D	48.07±2.84^{b} C	65.40±6.03^{b} B	100±0^{a} A	100±0^{a} A	100±0^{a} A	62.89±5.72 b
	FB	0±0^{a} E	0±0^{dD}	15.13±1.60^{d} C	19.71±1.16^{e} B	100±0^{a} A	100±0^{a} A	100±0^{a} A	47.83±6.16 c
	FC	0±0^{a} E	44.00±4.19^{a} D	55.53±2.5^{aC}	73.53±2.82^{a} B	100±0^{a} A	100±0^{a} A	100±0^{a} A	67.95±5.28 a
	FO	0±0^{a} D	0±0^{dD}	4.83±0.56^{eC}	25.42±2.05^{d} B	100±0^{a} A	100±0^{a} A	100±0^{a} A	47.18±6.27 c
	FP	0±0^{a} D	0±0^{dD}	14.08±1.24^{d} C	24.96±1.62^{d} B	100±0^{a} A	100±0^{a} A	100±0^{a} A	48.43±6.12 c
	Mean	0±0^{E}	14.36±2.49^{D}	25.79±3.13^{C}	40.21±3.66^{B}	100±0^{A}	100±0^{A}	100±0^{A}	55.55±2.45

LSD at 0.05 for:	*Meloidogyne incognit*	*Tylenchulus semipenetran*s
LSDT	1.97	1.31
LSDP	2.13	1.42
LSDTP	5.22	3.47

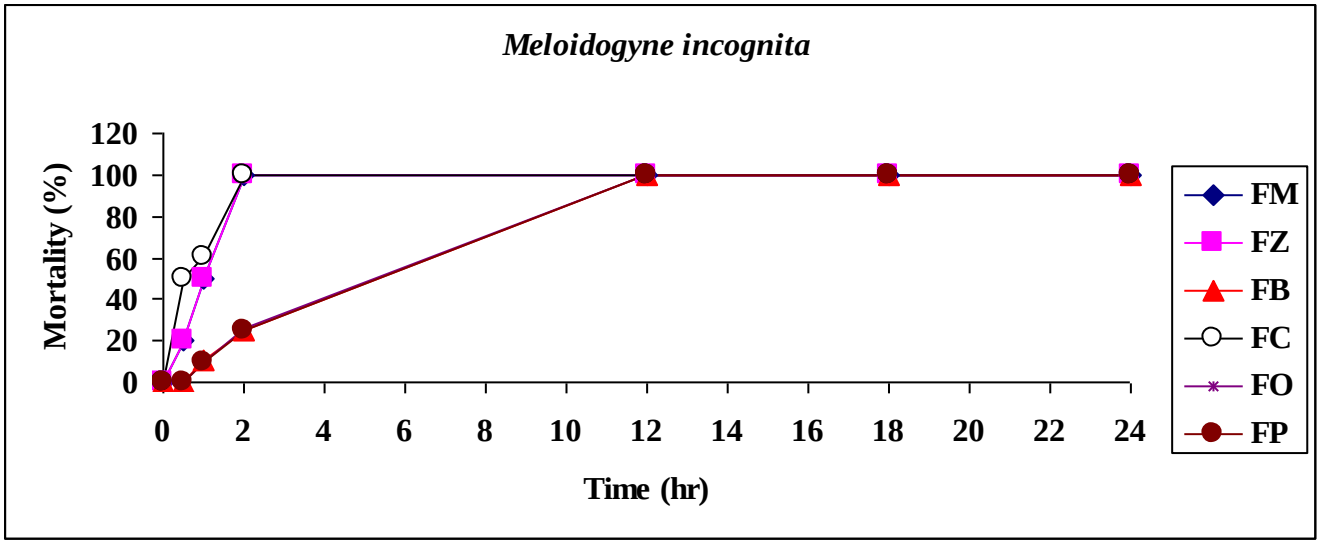

Fig. (14): Impact of tested furfural derivatives at concentration of 0.375% on Juveniles mortality% of *Meloidogyne incognita*.

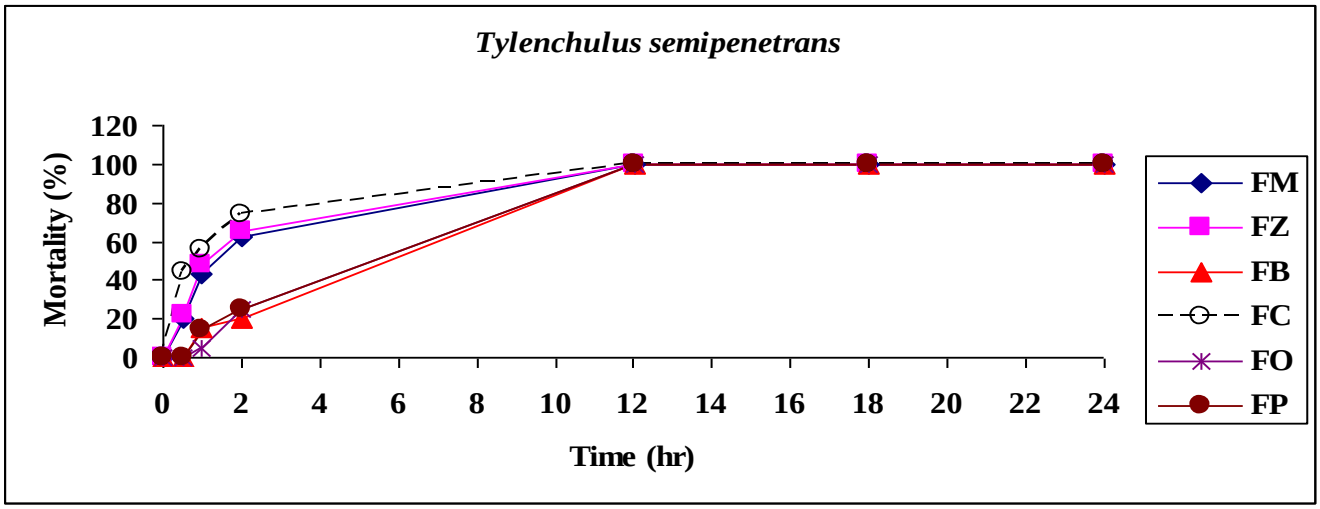

Fig. (15): Impact of tested furfural derivatives at concentration of 0.375% on Juveniles mortality% of *Tylenchulus semipenetrans*.

4. Discussion

For many years, chemical nematicides such as methyl bromide, metam sodium, and chloropicrin have been widely used to manage plant-parasitic nematodes and other soil-borne pathogens. However, the harmful environmental and health effects of these chemicals have raised significant concerns. These nematicides are known to contaminate agricultural ecosystems—polluting the soil, air, and water—while disrupting the balance of beneficial microflora and microfauna. They can also interfere with plant nutrient uptake and negatively affect non-target organisms, including bees and humans.

As a result of these adverse impacts and increasing regulatory restrictions, there is an urgent need to develop alternative, environmentally friendly strategies for managing soil-borne pests and diseases. Recent efforts have focused on eco-friendly approaches such as biocontrol agents, cultural practices, and the use of green chemicals derived from natural sources.

Furfural (2-furancarboxaldehyde) is a naturally occurring aromatic aldehyde found in some essential oils of plants. It is industrially produced from organic agricultural residues [20]

Furfural also is a promising contact nematicide [21] with degrading and destruction ability on nematode cuticle [16, 22, 23].

Furfural has emerged as a promising candidate in this context. It is a bio-based compound that is inexpensive, readily biodegradable by soil microorganisms, and relatively safe for humans and plants. **[8]** identified furfural as a potential replacement for banned Class I nematicides. Although foundational knowledge about its effects on economically significant nematodes is still limited, **[22]** proposed that furfural disrupts the nematode cuticle.

[23] investigated the nematicidal action of Cropguard®, a furfural-based product, on the ultrastructure of *Meloidogyne incognita* and *M. javanica*. After 96 hours of exposure, J_2 juveniles appeared sunken with more defined transverse striations, though the cuticle remained structurally intact.

Further studies have shown that furfural exposure leads to morphological deformities in J_2 larvae, such as shrunken, wrinkled cuticles and body contractions, especially in the head and body regions. This may be due to furfural acting as a solvent that dissolves the lipid layer of the egg shell or cuticle. This disruption increases permeability, resulting in cuticle damage and dehydration. Thus, prolonged exposure is crucial to enhancing furfural's nematicidal efficacy by maximizing its impact on the cuticle and reducing both J_2 viability and egg hatchability. **[8]**

To date, there are no published studies on the effects of furfural derivatives specifically on J2 mortality of plant-parasitic nematodes. Our study contributes novel insights in this regard. We found that even at very low concentrations, furfural derivatives were highly effective in reducing J_2 populations of both *Meloidogyne incognita* and *Tylenchulus semipenetrans* **(Table 3; Figures 13 and 14),** in contrast to earlier studies that focused solely on furfural or its formulations.

Using in vitro assays, we evaluated six furfural derivatives with potential nematicidal properties. The results clearly showed that all tested concentrations significantly increased J_2 mortality of both nematode species, particularly within the first 12 hours of exposure. These findings highlight the strong potential of furfural derivatives as bio-nematicides.

Further research is necessary to evaluate the effectiveness of these promising compounds under greenhouse and field conditions, as well as to investigate their modes of action at the physiological and molecular levels in plant-parasitic nematodes.

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