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RESEARCH ARTICLE

Combined effect of seed treatment on chemical constituents of root exudates in Chilli cv. PLR 1

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Abstract

A well-recognized spice and vegetable crop, chilli (*Capsicum annuum* L.) is prized for its color, flavor and nutritional content. Chillies are frequently grown in warm temperate, tropical and subtropical regions. It is indigenous to tropical South America and is a member of the Solanaceae family. One of the causes of the low chilli output is the slow and irregular germination of chilli seeds. Chilli seeds can germinate slowly and inconsistently for a variety of reasons. The two most important elements are illnesses and pests. Even while many insecticides and fungicides shield plants from diseases, it is impossible to overlook the buildup of residues in the economy and their effects on soil microorganisms, both positive and negative. The present study was conducted to analyze volatile compounds in treated chilli plants. Root exudates were collected and analyzed from 15 and 30 day old seedlings. GC-MS analysis revealed that seedlings treated with seeds produced a greater number of volatile compounds than the control samples. Specifically, treated seedlings emitted volatile compounds such as Hexadecanoic acid methyl ester (31.73%), 1-Hexadecanol (25.65%) and Benzaldehyde (16.42%) at 15 days, compared to 32.19% Hexadecanoic acid methyl ester and 26.42% Benzaldehyde in control seedlings. These compounds are known for their antifungal and antimicrobial properties. Additionally, germination rates showed a slight improvement in treated seeds (82%) compared to control seeds (80%), while vigor index values for treated seeds were 1148, compared to 1192 for control. Dry matter production was slightly higher in treated seeds (10.8 mg/10 seedlings) versus control (10.2 mg/10 seedlings). Notably, the root exudates of 15-day-old seedlings emitted 65 volatile compounds, significantly more than the 20 compounds emitted by the 30-day-old seedlings. These findings emphasize the dynamic nature of root exudates during early plant development and the potential role of seed treatments in influencing volatile compound profiles.

Keywords

chilli; germination; root exudates; vigour index; volatile compounds

Introduction

From an economic perspective, chillies are a very important and lucrative crop all over the world. It is thought that chiles are indigenous to New Mexico. The Portuguese brought chiles from Brazil to the Indo-Pak subcontinent before 1585. A significant spice crop grown all over the world for its color and pungency is the chilli (*Capsicum annuum*). The fruit's skin and septa contain capsaicin, the active component that causes the pungency and it is also utilized in the production of beverages and medications (1). India is the biggest producer, exporter and user of chiles worldwide. The area under chilli cultivation in India has varied from 634 to 921 thousand hectares over the last three decades. In 2023, India produced about two million metric tons of chilli. Tamil Nadu, Orissa, Karnataka, Maharashtra and Andhra Pradesh are the primary chilli-growing states in India.

One of the causes of the low chilli output is the slow and irregular germination of chilli seeds. Chilli seeds can germinate slowly and inconsistently for a variety of reasons. Disease is the most common factor among the others. Numerous diseases that affect chili are brought on by bacteria, viruses, nematodes, fungi and abiotic stressors (2). The invasion of numerous insect pests and mites at various crop stages is one of the biggest concerns when it comes to the limitations of chilli farming. The primary sucking pests of chilli in the Cuddalore District of Tamil Nadu are thrips (*Scirtothrips dorsalis* Hood), aphids (*Myzus persicae* Sulzer, *Aphis gossypi* Glover), as well as mites (Polyphagotarsonemus latus Banks), according to surveys (3).

Many insect pests attack the chilli crop from germination to harvest; among these, thrips are a prominent sucking insect pest that causes low productivity and decrease production by up to 50 % (4, 5). However, insect pests of chillies cause yield losses ranging from 50 to 90 % (6, 7). Through direct feeding, these sucking pests do significant harm to the chilli crop and spread the fatal chilli leaf curl disease. Thrips eat by sucking and rasping the leaking cell sap from the ventral side of the leaves, developing shoots, fruits and flowers. This is how both adults and nymphs eat. The afflicted leaves curl and display the distinctive symptoms of leaf curl.

Pre-sowing seed treatments in wheat have been found to influence both seedling growth rates and the composition of root exudates. These treatments reduce the intensity of root exudate production and alter their chemical composition, which impacts seedling growth dynamics (8). Root exudates are essential in shaping the rhizosphere microbiota, acting as carbon sources for soil microorganisms. By modifying these exudates, seed treatments can help promote beneficial microbial communities, including plant-growth-promoting bacteria (PGPB), which enhance plant growth and resilience (9).

Root exudates are chemicals that are exuded into the soil by roots. Roots can alter the chemical and physical characteristics of the soil, prevent the establishment of rival plant species, withstand herbivores, promote advantageous symbioses and control the local soil microbe community by releasing a range of chemicals (10). Root metabolite concentrations might vary throughout the root tip. Control of meristematic activity, phloem loading, root exudate re-uptake, as well as modulation of efflux transporter expression in roots are the principal mechanisms that link the soil microenvironment surrounding the root tips and the process of root exudation. Altering this flow can alter the solutes' temporal concentrations at the root tip, which will alter the architecture of the root system and enable the root to grow in response to external stimuli. In actuality, a large amount of root exudates are composed of 3 chemical groups: amino acids, organic acids and sugars. The production of lateral roots and the root meristem can be identified by several methods, resulting in diverse reactions in the architecture of the root system.

Root exudates significantly influence the composition and structure of bacterial communities in the rhizosphere (11). They perform critical functions, including serving as a defense mechanism against harmful microorganisms, attracting beneficial microbes through chemotaxis, maintaining soil moisture, mobilizing nutrients, altering soil chemical properties, stabilizing soil aggregates near roots and inhibiting the growth of competing plants (12). Plant roots continuously release a range of substances, including ions, free oxygen, water, enzymes, mucilage and various primary and secondary metabolites into the rhizosphere. These compounds, particularly carbon-containing substances, play a pivotal role in shaping microbial interactions in the root zone (10). The primary metabolites, such as sugars, amino acids and organic acids, are generally released passively and provide essential nutrients for rhizosphere-dwelling bacteria (13) (Fig. 1).

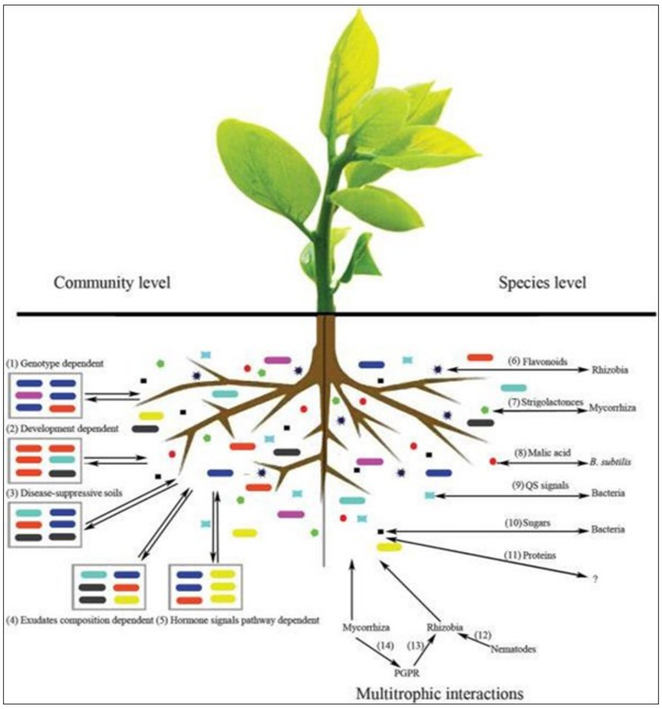


Fig. 1. Rhizospheric interactions are mediated by plant root exudates: At the community level (left), at the species level (right) and the multitrophic interactions level (bottom). http://www.nrcresearchpress.com/doi/full/10.1139/cjb-2013-0225

This study aims to understand the interaction between seed treatments and root exudates in chilli (*Capsicum annuum* L.) by demonstrating the influence of seed coating with Thiamethoxam on the production and composition of volatile compounds in root exudates. The research highlights the dynamic changes in volatile profiles between treated and untreated seedlings, with treated seedlings exhibiting a significant increase in the diversity and quantity of bioactive volatile compounds. These findings provide insights into how seed treatments can enhance plant-microbe interactions, improve defense mechanisms and potentially contribute to sustainable agricultural practices by reducing dependency on chemical pesticides and fertilizers.

Materials and Methods

Seed treatment

After coating the seeds with a solid-based formulation of thiamethoxam 35 FS (30 mL/kg), they were shade-dried at room temperature (30±2°C). A control treatment without any seed coating was also maintained. The germination test was conducted using the roll towel method with four replications (14). The chilli variety PLR1 was procured from the Vegetable Research Station, Plaur, TN, India.Thiamethoxam was chosen for seed treatment due to its systemic insecticidal properties, providing protection against soil-borne pests and early-stage insect infestations. The quantity of 30 mL/kg ensures effective pest control while minimizing phytotoxicity, based on recommended dosages. Its mechanism of action involves binding to nicotinic acetylcholine receptors, disrupting insect nerve transmission and leading to paralysis and death. Thiamethoxam is absorbed by the plant, offering long-lasting protection during early growth stages. This helps in reducing pest damage and supports healthier plant development for improved yield potential.

Preparation of root exudates

Following surface sterilization with ethanol at a concentration of 80% for five minutes and four rinses with distilled water, the chilli seeds were positioned in a paper medium for germination. The uniformly sized seedlings that had germinated were placed in glass test tubes with 50 mL of Hoagland's nutrient solution, which was made from deionized water. Root exudates had been taken at intervals of 15 and 30 days. A 20 mm diameter column filled with 100 mL of XAD-4 resin was used to filter the collected liquid. It was then eluted with 50 mL of methanol as well as condensed at 40°C using a rotary evaporator (Model IRA@ RV10). After that, 25 mL solution was kept in a refrigerator at -20°C until it was needed.

Identification of root exudates

To allow the methanol to naturally evaporate, 5 mL of concentrated methanol solution was transferred to a 200 mL XAD-4 resin column of 80% ether + 20% acetate elution. One millilitre of HPLC-grade methanol was used to dissolve the eluate after it had been vacuum-concentrated until it was dry (15). Through GC-MS (gas chromatography-mass spectrometry. GCAgilent-7890B, MSAgilent-5977A MSD) analysis, the primary component was utilized to identify the root exudates. Under the following events, 1 µL aliquot of the reaction mixture was directly injected into the GC: The GC runtime lasted 30 min, commencing at 80°C and rising to 250°C at a rate of 8°C/min, then reaching 300°C at a rate of 12°C/min and maintained for 5 min. The temperature of the injector was 240°C. Volatile compounds were classified based on their chemical structure (e.g., terpenes, aldehydes, alcohols) and identified using retention time and mass spectrometry. Biological activities were assessed through known effects such as antimicrobial, antifungal and plant growth-promoting properties. Compound concentrations were quantified to evaluate their potential biological impact. Comparative analysis across samples highlighted the most biologically significant compounds.

Results

The experiment showed that coated and control seeds were on par with the physiological quality parameters. The coated seeds recorded the highest germination (82%), total seedling length (14.0 cm), root length (8.3 cm) and shoot length (5.7 cm), vigor index (1148), dry matter production was found to be significantly higher in T3 treatment (10.8 mg/ 10 seedlings) and pathogen infection (8%) contrasted to control (Table 1) (Fig. 2). Finding volatile chemicals in the root exudates of K1 variety chilli seedlings that are 15 days old: The substances found in the

Fig. 2. Photographs representing the germination potential of control and coated chilli seeds.

Table 1. Effect of seed treatment with thiamethoxam on seedling establishment

Treatments	Germination (%)	Root length (cm)	Shoot length (cm)	Total seedling length (cm)	Vigour index	Dry matter production (mg 10 seedlings^{-1})	Seed health (Pathogen infection) (%)
Control	80	8.5	6.4	14.9	1192	10.2	12
Coating (30mL/kg)	82	8.3	5.7	14.0	1148	10.8	8

root exudates of the control seedlings were displayed in (Table 2) and (Fig. 3). The primary chemical components were Hexadecanoic acid, methyl ester (32.19%), Benzaldehyde (26.42), 1,2-Dimethyl-4- nitro-5-6-pyrrolidinoimidazole (14.77), 15-methyl, methyl ester (4.01), Hydroxylamine (3.52), Benzeneethanamine (2.45), Pyrrilidine-2-thione (2.05) and 1,3,3-trimethyl-2-(methyl-2-methylene-3-heaxadexa-1,6,10,14-tetraene) (1.76%) were identified control seeds of 15th day chilli seedling.

A total of sixteen chemical compounds were found in treated seeds (Fig. 4, Table 3) at 15th seedlings. Antifungal activity was present in 31.73 % of the compounds that were identified. The primary chemical components that have the highest peak area percentage of Hexadecanoic acid, methyl ester (31.73), 1-Hexadecanol (26.65), 1,2-Dimethyl-4- nitro-5-6-pyrrolidine imidazole (25.65), Benzaldehyde (16.42), 2-(2-Furyl)-4- Tris methoxy carbonylmethoxy-6 (9.59%), Acetaldehyde (3.69), 15-methyl, methyl ester (3.69%), 4-dicyano-5methlbiphenyl (2.21%). The varied compounds identified in treated seeds of 15th day seedlings root exudates were 2-(2-Furyl)-4- (Tris methoxycarbonyl methoxy-6), Methoxyamine hydrochloride, 1,4-dioxane-2-carboxylate, 4-dicyano-5methlbiphenyl and Acetaldehyde.

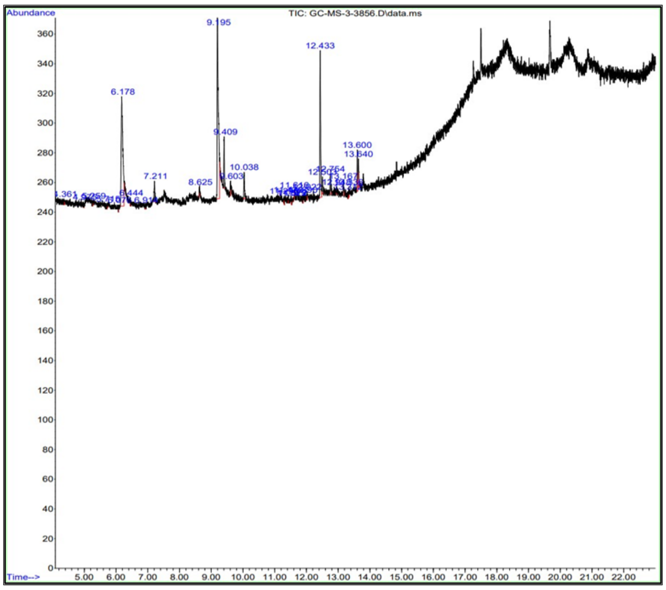
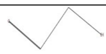
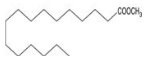
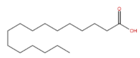
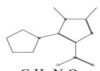
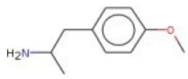
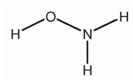
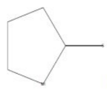
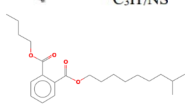
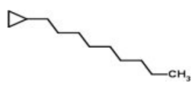
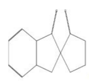


Fig. 3. GC-MS chromatogram of root exudates from 15th day old untreated chilli seedlings.

Table 2. Root volatile compounds of control chilli seedlings on 15th day

S. No.	Retention time	Name of the compounds	Areaper cent	Nature of the compounds	Compound structure	Biologicalactivity
1.	9.195	Hexadecanoic acid, methyl ester	32.19	Ester	 $C_2H_4O_2$	Antibacterial, antifungal
2.	6.178	Acetaldehyde,Benzaldehyde	26.42	Aldehyde		Antifungal, antimicrobial
3.	12.433	1,2-Dimethyl-4-nitro-5-6-pyrrolidine imidazole	14.77	Imidazole		Antifungal
4.	9.409	15-methyl, methyl ester	4.01	Ester	 $C_9H_{14}N_4O_2$	Antioxidant, nematicide
5.	13.600	Hydroxylamine	3.52	Amine		Antioxidants
6.	10.038	Benzeneethanamine	2.45	Phenylethylamine		Antifungal
7.	7.211	Pyrrolidine-2-thione	2.05	Thione	 C_3H_7NS	Antifungal
8.	13.640	1.2- Benenedicarboxylic acid, methylester	1.96	Ester		Antifungal
9.	12.754	1,3,3-trimethyl-2-(methyl-2-methylene-3- heaxadexa 1,6,10,14-tetraene)	1.76	Terpene	 $C_{20}H_{32}$	Antimicrobial
10.	11.298	Cyclopropane	1.65	Cycloal-kane		Antifungal
11.	12.503	3-Chloro-1-propene	1.57	Alkene	 C_3H_5Cl	Antibacterial, antifungal, Promotes seed germination
12.	9.603	Spiro [indane-2,2’-cyclopentane]-1,1-dione	1.47	Dione	 $C_{13}H_{12}O_2$	Antifungal
13.	13.167	1-Hexadecanol	1.27	Alcohol		Antibacterial, antifungal

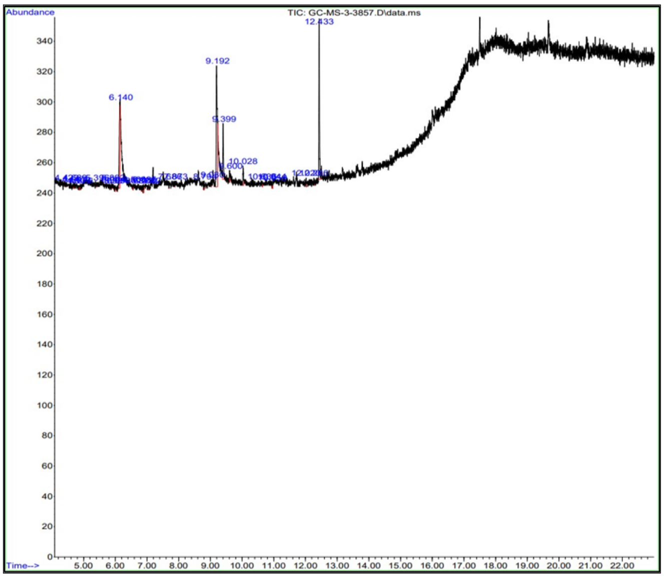
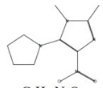
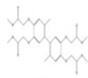
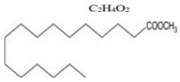
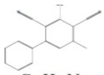
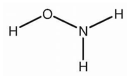
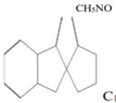
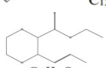
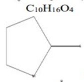
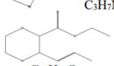


Fig. 4. GC-MS chromatogram of root exudates from 15th day old, treated chilli seedlings.

Table 3. Root volatile compounds of treated chilli seedlings on 15th day

S. No.	Retention time	Name of the compounds	Area per cent	Nature of compounds	Compound structure	Biological activity
1.	9.192	Hexadecanoic acid, methyl ester	31.73	Ester		Antibacterial, antifungal
2.	12.433	1-Hexadecanol	25.65	Alcohol		Antifungal, antimicrobial
3.	12.433	1,2-Dimethyl-4-nitro 5-6-pyrrolidine imidazole	25.65	Imidazole	 $C_9H_{14}N_4O_2$	Antifungal,
4.	6.140	Benzaldehyde,Acetaldehyde	16.42	Aldehyde	 $C_2H_4O_2$	Antifungal, antimicrobial
5.	9.399	2-(2-Furyl)-4-(Tris methoxycarbonyl methoxy-6)	9.59	Ester	 $C_{26}H_{30}O_{12}$	Antifungal
6.	9.012	1-Hexadecanol	8.75	Alcohol		Antibacterial, antifungal
7.	10.028	Acetaldehyde	3.69	Aldehyde	 $C_2H_4O_2$	Antifungal, antimicrobial
8.	11.82	15-methyl, methyl ester	7.91	Ester		Antioxidant, nematicide
9.	9.600	4-dicyano-5- methlbiphenyl	2.21	Phenyl	 $C_{15}H_{11}N_3$	Antibacterial, antifungal
10.	8.640	1- Propene-3 -chloro	2.02	Alkene	 C_3H_5Cl	Antibacterial, antifungal
11.	6.885	Hydroxylamine	1.11	Amine		Antioxidants
12.	6.993	Methoxyamine hydrochloride	1.06	Amine	 CH_5NO	Antifungal
13.	10.636	Spiro [indane-2,2'cyclopentane]-1,1-dione	0.55	Dione	 $C_{13}H_{12}O_2$	Antifungal
14.	6.561	Ethyl3-propenyl-1,4-dioxane-2-carboxylate	0.37	Dioxane	 $C_{10}H_{16}O_4$	Antifungal
15.	7.873	Pyrrolidine-2-thione	0.37	Thione	 C_3H_7NS	Antifungal
16.	5.891	1,4-dioxane-2 carboxylate	0.18	Dioxane	 $C_{10}H_{16}O_4$	Antibacterial, antifungal

Characterized the volatile substances in the root exudates of 30-day-old chilli seedlings

Fig. 5 and Table 4 display the volatile chemicals that were found in the control seedlings. 1.42 % of the compounds that were found had antifungal activity. The major volatile compounds of Methyl ester (23.60%), n-decanoic acid (9.81%), 1,6-Octadiene (6.99%), Thiophene- 2-Acetamide (4.78%), Hydroxylamine (3.84 %), Methylpent-4- phenylamine (3.79%) and Tridecane -10-carboxylic acid (3.05%).

Fourteen volatile compounds (Fig. 6, Table 5) have been identified from coated seeds. Among the identified compounds 3.97 % had insecticidal activity. The major percentage of volatile compounds were found in coated seeds: Acetaldehyde (17.06 %), 7,11-Trimethyl-dodeca-2,4,6 -tetraenal (11.83%), Phenol (10.90%), Tert- Hexadecanethiol (3.97 %), Phenylephrine (3.63%) and methyl ester (2.72%).

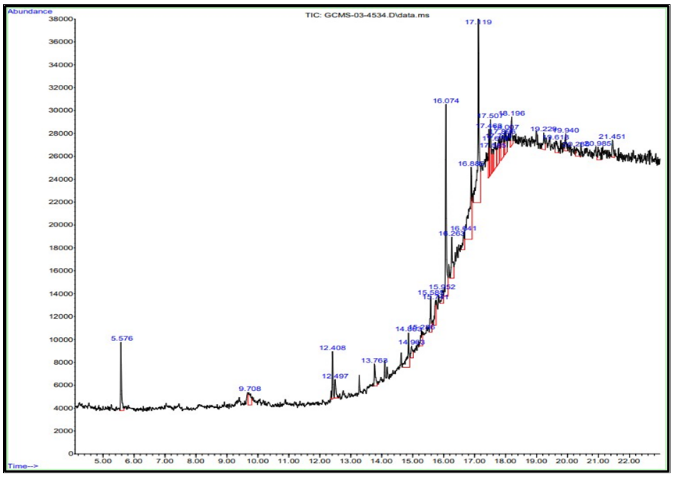


Fig. 5. GC-MS chromatogram of root exudates from 30th day old untreated chilli seedlings.

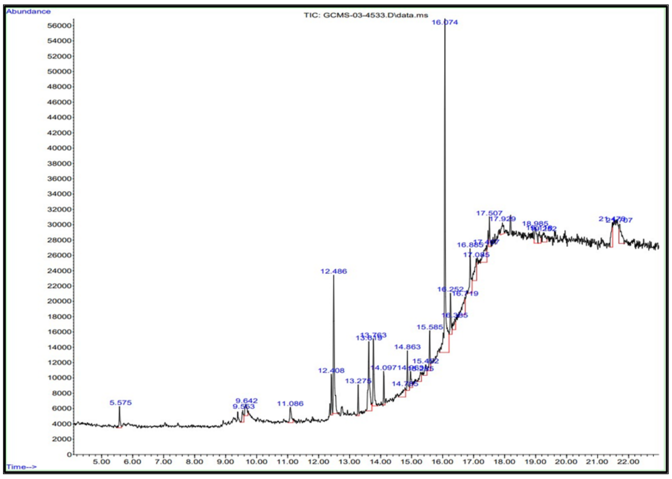


Fig. 6. GC-MS chromatogram of root exudates from 30th day old, treated chilli seedlings.

Table 4. Root volatile compounds of control chilli seedlings on 30th day

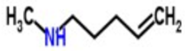
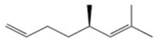
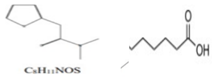
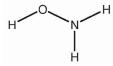
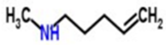
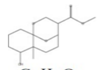
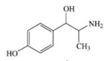
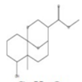
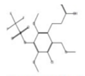
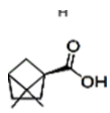
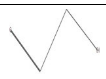
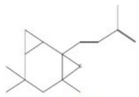
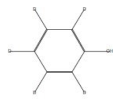
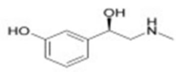
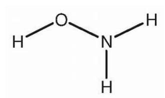
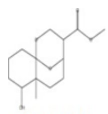
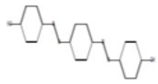
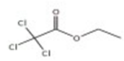
S. No.	Retentiontime	Name of the compounds	Area per cent	Nature of compound	Compoundstructure	Biologicalactivity
1	16.074	Methyl ester	23.60	Ester	 $C_{12}H_{22}O_4$	Antifungal, antimicrobial,anti-bacterial
2	12.486	n-decanoic acid	9.81	Fatty acids		Antioxidant, nematicide,
3	13.619	1,6-Octadiene	6.99	Alkene		Antioxidant
4	13.763	Thiophene-2-Acetamide	4.78	Amide	 $C_8H_{11}NOS$	Antimicrobial
5	16.885	Hydroxylamine	3.84	Amine		Antioxidants
6	17.407	Methylpent-4-phenylamine	3.79	Amine		Antibacterial
7	17.085	Tridecane -10-carboxylic acid	3.05	Ester	 $C_{14}H_{22}O_5$	Antifungal
8	21.473	P-Hydroxy-norephedrine	2.66	Phenethylamines		Antibacterial
9	12.408	Acetaldehyde	2.25	Aldehyde	 $C_2H_4O_2$	Antifungal, antimicrobial
10	18.985	T-trimethyl-silylester	2.18	Ester	 $C_{14}H_{22}O_5$	Antifungal, antimicrobial, anti bacterial
11	14.863	Methyl 3- Hydroxy-3-Phenyl Dithiopropanoat	2.09	Phenyl	 $C_{14}H_{16}ClF_3O_8S$	Antimicrobial
12	11.086	1-Hexadecanol	1.86	Fatty acids alcohol		Antibacterial
13	17.507	"Trans-Undec-4-enal	1.51	Aldehyde		Antimicrobial
14	5.575	Bicyclo [2.1.1] hexane -1-carboxylic acid, 5,5- dimethyl	1.42	Carboxylicacid		Antifungal"

Table 5. Root volatile compounds of coated chilli seedlings on the 30th day

S. No.	Retention time	Name of thecompounds	Area percent	Nature of compound	Compoundstructure	Biologicalactivity
1.	17.119	Acetaldehyde	17.06	Aldehyde	 $C_2H_4O_2$	Antifungal, antimicrobial
2.	16.885	7,11 Trimethyl-dodeca-2,4,6-tetraenal	11.83	Ketone	 $C_{15}H_{22}O$	Antimicrobial
3.	16.074	Phenol-d6	10.90	Phenol	 C_6HD_5O	Antimicrobial
4.	14.863	Tert-Hexadecanethiol	3.97	thiol	 $CHAgF_3S$	Antioxidant, insecticidal
5.	5.576	Phenylephrine	3.63	Phenethyla-mines		Antibacterial
6.	17.463	Methyl ester	2.72	Ester	 $C_{17}H_{34}O_2$	Antifungal, antimicrobial,anti bacterial
7.	12.497	Hydroxylamine	2.38	Amine		Hydroxylamine
8.	12.408	1-Hexadecanol	2.20	Fatty alcohol		Antibacterial
9.	18.007	Tetrapentacontane	2.11	Hogen-atedalkane		Antimicrobial
10.	9.708	Tridecane -10-carboxylic acid	1.81	Ester	 $C_{14}H_{22}O_5$	Antifungal
11.	15.286	1,4- Bis (4 hydroxyphenyl) benzene	1.63	Benzene	 $C_{18}H_{14}N_4O_2$	Antifungal, antimicrobial, antibacterial
12.	21.451	Acetic acid, trichloro-nonylester	0.41	Ester		Pesticide

The diverse compounds identified in coated 30 days seedlings root exudates were Phenylephrine, 1-Hexadecanol Tert-Hexadecanethiol, 1,4-Bis (4-hydroxyphenyl) benzene, 7,11- Trimethyl- dodeca-2,4,6-tetraenal, Tetrapentacontane and Acetic acid, trichloro-nonyl ester (Table 5) compared control. Hydroxylamine, hexadecanoic acid, methyl ester and 1-hexadecanol were the major chemicals found in the root exudates of seedlings that were 15 and 30 days old.

Discussion

Compounds play a significant role in biological systems, such as helping plants survive adverse environmental conditions. Tetradecanoic acid and hexadecanoic acid are fatty acids recognized for their potential antibacterial and antifungal properties, suggesting their applicability in traditional medicine for treating various ailments. Tetradecanoic acid, also known as myristic acid is considered to have significant nutritional value, making it suitable for consumption (16). Hexadeconic acid is recognized to possess nematicide and antioxidant properties (17). Hexadecanoic acid methyl ester exhibits antioxidant properties and is also associated with hypercholesterolemic effects and potential use as a pesticide (18). Alcohols with antifungal properties, like 1-hexanol, can prevent diseases (19). Hydroxylamine compounds facilitate seed germination by hindering the breakdown of hydrogen peroxide (H_2O_2) through catalase inhibition and it exhibits robust reducing properties and acts as a potent chelating agent (20, 21). When reacting with aldehydes and ketones, it forms oximes, or when mono-N is substituted, it generates nitrogen ethers with aldehydes. The notable chelation abilities of hydroxylamine towards the iron atoms present in haem proteins, alongside its discernible albeit reduced capacities with N-aliphatic substituted hydroxylamines, suggest the existence of similar actions within seeds. Since the fungal membrane is essential for preserving cell integrity as well as order, antifungal treatments primarily "target the fungal membrane (22). The mechanism through which antifungal fatty acids directly interact with the fungal cell membrane was uncovered (23). 3-pyrazolylalanine" had been only identified in early stages of cucumber root exudates. It was noted that the exudation by oat roots was enhanced by cultured filtrates of certain bacteria, fungi, as well as antibiotics (24, 25). Bacterial volatiles can hinder the growth of other microbes and have antibacterial properties (26–29). Thiamethoxam influences root exudate profiles by activating hormonal pathways, enhancing primary and secondary metabolism, modulating efflux transporters and improving microbial interactions. These biochemical changes result in a dynamic rhizosphere environment that enhances plant growth, stress resilience and nutrient acquisition. This multifaceted impact highlights the potential of thiamethoxam as a seed treatment to improve plant performance and sustainability in agriculture (30).

Several fatty acids exhibit potent antifungal properties, primarily by disrupting fungal membranes. For instance, the antifungal action of (Z)-9-heptadecenoic acid against fungi such as *Phytophthora infestans* and *Idriella bolleyi* has been shown to cause plasma membrane disintegration or damage, attributed to hydrostatic turgor pressure within the fungal cell (23). These antifungal fatty acids present a sustainable alternative to synthetic chemicals currently used to control plant diseases, which often negatively impact ecosystems by affecting non-target organisms (31). The production of volatile compounds in plants is influenced by the age of seedling roots and various factors, including root structure, cytosolic concentration, membrane permeability, microbial signaling, photosynthesis, evaporation, transpiration, carbon allocation from shoots to roots, developmental stage, herbivory on shoots and allelochemical release (32).

The GC-MS analysis of root exudates from treated and untreated chilli seedlings revealed significant differences in the volatile compound profiles at both 15 and 30 days of growth. Key alterations in the composition of root exudates were observed between the treated and untreated groups, particularly in terms of compound diversity and intensity. These changes suggest that seed treatments can influence plant-microbe interactions and potentially improve plant resilience or growth by altering root exudation. Our study demonstrates that volatile compounds play a critical role as energy sources and signaling molecules, inducing the production of secondary metabolites. Notably, both control and coated seeds emitted a variety of volatile compounds; however, coated seeds released a distinct profile of volatiles compared to control seeds. These unique volatiles from coated seeds contributed to maintaining plant health under adverse environmental conditions.

Conclusion

The GC-MS analysis revealed that the volatile compounds commonly present in both 15-day-old and 30-day-old chilli seedlings included Hydroxylamine, Hexadecanoic acid methyl ester and 1-Hexadecanol. Root exudates from both age groups of coated seedlings released a comparable number of volatile compounds as the control. However, seeds coated with Thiamethoxam 35 FS emitted a distinct array of compounds compared to the control, without adversely affecting germination percentages. Notably, antifungal and antimicrobial compounds were predominantly released by the 15-day-old and 30-day-old seedlings. These findings have significant implications for sustainable agriculture. The antifungal and antimicrobial volatile compounds identified, such as Hydroxylamine and Hexadecanoic acid methyl ester, can be utilized in biocontrol strategies to manage plant pathogens. Their natural origin makes them ideal for organic farming, reducing dependency on synthetic pesticides. Additionally, these bioactive compounds could enhance crop resilience while promoting soil health and biodiversity.

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Authors' contributions

VVG carried out the entire study. KS helped in plant protection studies. KP helped in formulation of treatment. SK helped in laboratory analysis. AT participated in the design of the study and performed the statistical analysis. MSA participated in the formatting the manuscript. EJ cross checked the references. ST SS and RN checked the plagiarism and aligned the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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