

Insight of organic fertilizers (OFs) with Fourier Transform Infrared (FT-IR) spectroscopy and antifungal activity

Nirmal Singh^a, Gulab Pandove^{b,*}, Anu Kalia^c, Amandeep Singh Sidhu^b, Ajay Kumar Choudhary^b & Urmil Gupta Phutela^d

^aDepartment of Microbiology, ^bSchool of Organic and Natural Farming,

^cElectron Microscopy and Nanoscience Laboratory, ^dDepartment of Renewable Energy and Engineering,
Punjab Agricultural University, Ludhiana 141 004, India

*E-mail: gpandove@pau.edu

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In the present investigation, the potential of FTIR spectroscopy has been explored to determine various functional groups in organic fertilizers (OFs) namely *Beejamrit* (BA), *Jeevamrit* (JA), *Ghanjeevamrit* (GJ), Biogas slurry (BS), Desi cow dung bioenzyme (DCDB), and Vermicompost (VC) that have role in plant growth promotion as well as has antimicrobial potential. The FTIR spectra divulged the occurrence of numerous functional groups named as methyl, carbonyl, hydroxyl, amines, phosphates, silicon or boron compounds, thiol, ester or amide groups in OFs. These functional groups regulate reactive oxygen, nitrogen and sulphur species, rhizospheric microbiome, plant microbe interactions by improving the nutrient uptake, thereby improves plant stress tolerance. The current research highlights the prominent potential of OFs (non-autoclaved and autoclaved) in inhibiting the growth of *Curvularia lunata*. It might be due to the presence of microorganisms and heat stable metabolites in OFs. *Beejamrit* showed the maximum inhibition (70%) among the evaluated autoclaved OFs. Whereas, in non-autoclaved OFs, *Jeevamrit* showed the maximum inhibition (95%). The outcome of the study divulged that OFs not only enhancing plant growth and productivity but also offers natural disease suppression (antimicrobial activity). Future research can investigate their synergistic effects, mechanisms and extensive applications.

Keywords: Antifungal efficacy, Biogas slurry, FTIR spectra, *Jeevamrit*, Organic fertilizer, Vermicompost

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The advent of intensive agricultural practices spurred by the Green Revolution has drastically reshaped traditional farming system shifting from age-old knowledge based methods to technology driven approaches aimed at improving productivity to meet dynamic increasing food demands. This revolution moved many regions from a status of food trader to being self-sufficient¹. On large scale chemical fertilizers have undeniably played crucial role in enhancing crop production but there misuse and over use and poor fertilizers possesses nutrient imbalances, soil depletion and accelerated environmental spoilage². In-addition, unwavering trust on these chemical inputs has altered soil profile through prolonged toxicity³. The organic fertilizers (OFs) release indispensable nutrients gradually in plant available forms including nitrogen, phosphorus and potassium that ultimately led to nutrient uptake and improved crop health⁴. Improvement in soil physiochemical, microbiological and biochemical properties can be obtained through the use of organic fertilizers. Organic

and INM systems, blending organic and selectively inorganic amendments are steadily becoming primary selection for their well-being which offers improved soil structure biodiversity outcomes with enhanced crop yields⁵. The use of organic waste as fertilizers not only significantly reduces the input cost but also nullifies pollution risks associated with soil and water⁶. Despite the environmental and agronomic advantages, organic nutrient fertilizers require targeted outreach and support through effective demonstration, awareness programs, and farmer training to maximize its adoption and impact. Keeping above points in view the Fourier transform infrared spectroscopy (FTIR) analysis of the 6 different organic fertilizers (OFs) such as *Beejamrit* (BA), *Jeevamrit* (JA), *Ghanjeevamrit* (GJ), Biogas slurry (BS), Desi cow dung bioenzyme (DCDB), and Vermicompost (VC) was carried out to identify the presence of the different functional groups in the OFs.

Material and Methods

In the present study, organic inputs such as *Beejamrit* and *Jeevamrit* were prepared following the method outlined by Mahanta and Dhar⁷, while *Ghanjeevamrit*

*Corresponding author

was prepared according to the procedure specified by Palekar⁸. The Vermicompost was sourced from School of Organic and Natural Farming and desi cow dung based bioenzyme was obtained from the Department of Renewable Energy and Engineering, PAU, Ludhiana.

Fourier Transform Infrared (FT-IR) spectroscopy of organic fertilizers

FT-IR spectroscopy is a versatile method for the determination of the functional group in the samples. The OFs were oven dried at 40°C for 2 days. The dried samples were transferred into screw cap vials to cool down to room temperature in a vacuum desiccator. Each of the dried samples were placed directly on the crystal of ETR assembly of FTIR spectroscope and were analyzed for the wave number ranging from 4000-400 cm^{-1} wave number.

In vitro evaluation of the antifungal activity of organic fertilizers against pathogenic fungi *i.e.* *Curvularia lunata*

The antifungal properties of BA, JA, GJ, BS, DCDB, and VC were assessed using the plate assay method⁹ against the pathogenic fungus *Curvularia lunata*. Potato Dextrose Agar (PDA) was selected as the growth medium due to its suitability for fungal cultures. Each sample (0.1 mL of *Beejamrit*, *Jeevamrit*, *Ghanjeevamrit*, biogas slurry, desi cow dung bioenzyme and vermicompost) was spread-plated onto sterile Petri dishes containing PDA, respectively. Approximately, 5 mm mycelial plug was excised from the peripheral edge of a five-day-old culture of *C. lunata* and positioned at the centre of each plate. The inoculated plates were then incubated at 30°C for seven days. The colony size of fungi was measured by Himedia colony size scale. The percentage inhibition was calculated following method¹⁰. In another set, the organic fertilizers were autoclaved before used, the rest of the procedure was same. In case of solid OFs, *i.e.*, vermicompost and ghanjeevamrit, a total of 1 g of each sample was mixed with 5 mL of sterilized distilled water and vortex. After two hours, it was centrifuged at 8000 rpm for 10 min and supernatant was used for further studies.

$$\text{The per cent inhibition was calculated as} = \frac{(\text{Growth of fungus in control plate}) - (\text{Growth of fungus in inoculated plate})}{\text{Growth of fungus in control plate}} \times 100$$

Results

Beejamrit, *Jeevamrit* and desi cow dung bioenzyme

The organic inputs such as BA, JA and DCDB are liquid organic formulations (Fig. 1-3). In the case of

Beejamrit and *Jeevamrit*, cow urine and cow dung served as the primary components. Similarly, desi cow dung bioenzyme used in the present study was produced by the fermentation of desi cow dung. The weak band observed at 3852.20, 3734.79, and

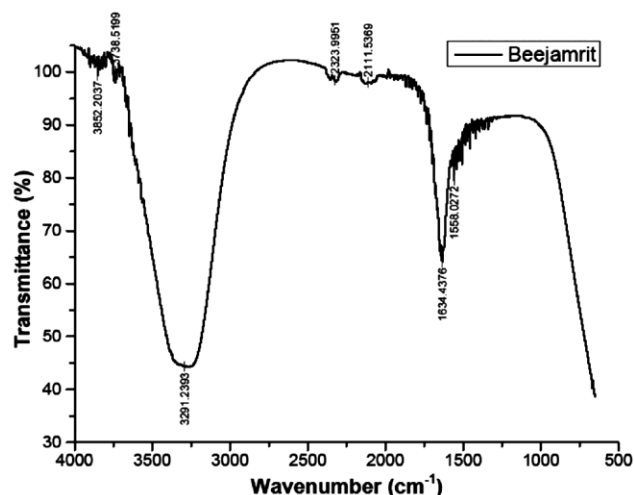


Fig. 1 — FT-IR interpretation of *Beejamrit*

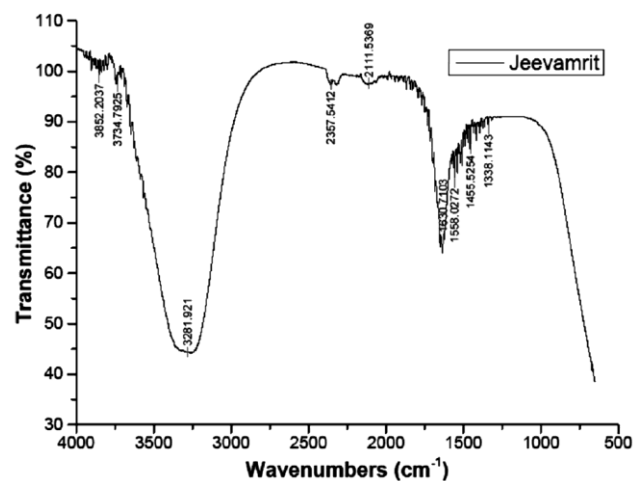


Fig. 2 — FT-IR interpretation of *Jeevamrit*

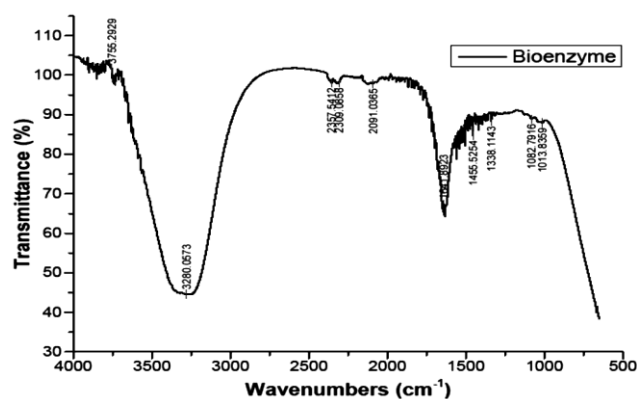


Fig. 3 — FT-IR interpretation of desi cow dung bioenzyme

3755.29 cm^{-1} in *Beejamrit*, *Jeevamrit*, and desi cow dung bioenzyme, respectively, was assigned to the C-H stretching vibrations. The broad and strong bands lying at 3291.23, 3281.92, and 3280.05 cm^{-1} in these organic formulations may correspond to the intramolecular bonded O-H stretching peak. Additionally, bands observed at 2323.99, 2357.54, and 2357.54 cm^{-1} in *Beejamrit*, *Jeevamrit*, and desi cow dung bioenzyme, respectively, may correspond to the S-H stretching vibrations. The small and weak band observed at 2111.53 cm^{-1} in *Beejamrit* and *Jeevamrit* and 2091.03 cm^{-1} in desi cow dung bioenzyme was likely attributed to Si-H stretching. Additionally, a medium-intensity band was observed at 1634.43, 1630.71, and 1641.89 cm^{-1} , indicating the presence of C=N stretching in amides within these organic fertilizers (OFs). The small and weak band observed at 1558.02, 1455.52, and 1455.52 cm^{-1} in *Beejamrit*, *Jeevamrit*, and desi cow dung bioenzyme, respectively, corresponds to the C-C stretching vibration of an aromatic ring compound. Another band observed at 1338.11 cm^{-1} in *Jeevamrit* and desi cow dung bioenzyme was due to the symmetrical and asymmetrical bending vibrations of the CH_3 (methyl) group (Table 1).

FT-IR analysis of Biogas slurry

Biogas slurry (BS) is a by-product of anaerobic digestion, consisting primarily of liquid digestate or anaerobic digestion effluent (Table 1 & Fig. 4). The weak and small band observed at 3846.61 cm^{-1} in the biogas slurry is assigned to C-H stretching vibrations. A broad and intense band located at 3309.87 cm^{-1} in the biogas slurry corresponds to the O-H and N-H stretching vibration due to intramolecular bonding. Additionally, small bands at 2314.67 cm^{-1} and 2368.72 cm^{-1} indicate the presence of silicon (Si-H stretching) and boron compounds. The peak at 1634.43 cm^{-1} in the biogas slurry may correspond to C=O stretching vibrations of esters. Medium-intensity bands at 1558.02- 1634.43 cm^{-1} are attributed to C=O stretching vibrations of carbonyl groups. Additionally, a band observed at 1455 cm^{-1} in the biogas slurry is linked to C-C stretching in aromatic ring compounds. A band at 1338.11 cm^{-1} in biogas slurry indicates C-N stretching vibrations in amines.

FT-IR analysis of *Ghanjeevamrit*

The primary component of *Ghanjeevamrit* is cow dung, making it essential to compare its FT-IR spectra with those of cow dung extracts to identify the organic constituents and functional groups (Table 1 &

Fig. 5). The FT-IR spectral analysis of *Ghanjeevamrit* revealed distinct functional groups. The weak and small bands observed between 3846.61 to 3591.29 cm^{-1} correspond to C-H stretching vibrations. Strong and broad bands centred at 3270.73 cm^{-1} were attributed to free O-H and N-H stretching vibrations. Additionally, broad bands between 2851.41 to 2918.50 cm^{-1} were linked to symmetric stretching vibrations of the CH_2 group. The small bands at 2314.67 and 2368.72 cm^{-1} in the *Ghanjeevamrit* indicate the presence of silicon (Si-H stretching) and boron compounds. The peak at 1634.43 cm^{-1} in the *Ghanjeevamrit* corresponds to the C=O stretching vibration of esters. The intense bands at 1539.39-1634.43 cm^{-1} in the *Ghanjeevamrit* are attributed to the C=O stretching vibrations of carbonyl groups. The band at 1233.74 and 1248.84 cm^{-1} in the *Ghanjeevamrit* may result from the C-N stretching vibrations of amines. The peak at 872.19 cm^{-1} represents P-O and P=O stretching vibrations of polyphosphates.

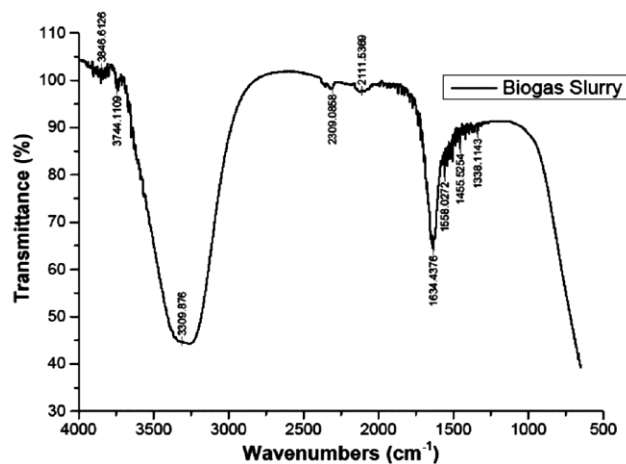


Fig. 4 — FT-IR interpretation of Biogas slurry

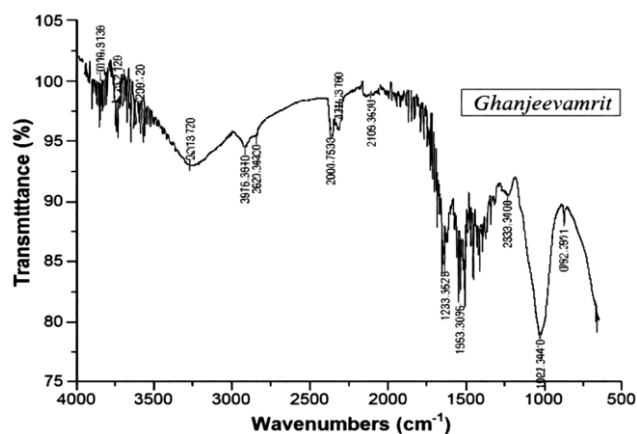


Fig. 5 — FT-IR interpretation of *Ghanjeevamrit*

Table 1 — Band distribution of organic fertilizers (OFs)

Band distribution of <i>Beejamrit</i> , <i>Jeevamrit</i> and desi cow dung bioenzyme			
S. No.	Functional group	Spectra range literature (cm ⁻¹)	Spectra range of <i>Beejamrit</i> , <i>Jeevamrit</i> and desi cow dung bioenzyme (cm ⁻¹)
1	C-H stretching	3625 cm ⁻¹ Sivam <i>et al.</i> ¹²	3852.20, 3734.79 and 3755.29 cm ⁻¹
2	O-H stretching	3413- 3421 cm ⁻¹ Rao ¹³	3291.23, 3281.92 and 3280.05 cm ⁻¹
3	S-H stretching	2524.62 cm ⁻¹ Suresh <i>et al.</i> ¹⁷	2323.99, 2357.54 and 2357.54 cm ⁻¹
4	Si-H stretching	2130.07 and 2076.35 cm ⁻¹ Socrates ²⁰	2111.53, 2111.53 and 2091.03 cm ⁻¹
5	C=N stretching in amides	1636.1 cm ⁻¹ Nautiyal and Dubey ²³	1634.43, 1630.71 and 1641.89
6	C-C stretching	1452.11 and 1455.17 cm ⁻¹ Anand and Suresh ²⁶	1558.02, 1455.52 and 1455.52 cm ⁻¹
7	CH ₃ (methyl) stretching	1383.12 cm ⁻¹ and 1394.20 cm ⁻¹ Ovchinnikov <i>et al.</i> ²⁷	1338.11 and 1338.11 cm ⁻¹ (in <i>Jeevamrit</i> and bioenzyme)
Band distribution of Biogas slurry (cm ⁻¹)			
8	C-H stretching	3625 cm ⁻¹ Sivam <i>et al.</i> ¹²	3846.61 cm ⁻¹
9	O-H and N-H stretching	3413- 3421 cm ⁻¹ Rao ¹³	3309.87 cm ⁻¹
10	Silicon (Si-H) stretching and boron compounds	2076.35 cm ⁻¹ -2130.07 cm ⁻¹ Socrates ²⁰	2314.67 and 2368.72 cm ⁻¹
11	C=O stretching vibration of esters	1759.41 cm ⁻¹ Yam <i>et al.</i> ³¹	1634.43 cm ⁻¹
12	C=O stretching vibrations of carbonyl groups	1632.84 - 1644.86 ⁻¹ Stewart ³²	1558.02- 1634.43 cm ⁻¹
13	C-C stretching in aromatic rings	1460 cm ⁻¹ Anand and Suresh ²⁶	1455 cm ⁻¹
14	C-N stretching vibrations of amines	1248.84 cm ⁻¹ Li <i>et al.</i> ³³	1338.11 cm ⁻¹
Band distribution of <i>Ghanjeevamrit</i> (cm ⁻¹)			
15	C-H stretching	3625 cm ⁻¹ Sivam <i>et al.</i> ¹²	3591.29- 3846.61 cm ⁻¹
16	O-H and N-H stretching	3413- 3421 cm ⁻¹ Rao ¹³	3270.73 cm ⁻¹
17	CH ₂ group	2830 and 2945 cm ⁻¹ Suresh <i>et al.</i> ¹⁷	2851.41 and 2918.50 cm ⁻¹
18	Silicon (SiH) stretching and boron compounds	2076.35 cm ⁻¹ -2130.07 cm ⁻¹ Socrates ²⁰	2314.67 and 2368.72 cm ⁻¹
19	C=O stretching vibration of esters	1759.41 cm ⁻¹ Yam <i>et al.</i> ³¹	1634.43 cm ⁻¹
20	C=O stretching vibrations of carbonyl groups	1632.84 - 1644.86 ⁻¹ Stewart ³²	1539.39- 1634.43 cm ⁻¹
21	C-N stretching vibrations of amines	1248.84 cm ⁻¹ Stehfest <i>et al.</i> ³⁶	1233.74 and 1248.84 cm ⁻¹
22	C-H bending or C-O and C-C stretching vibrations of carbohydrates	1000 cm ⁻¹ Li <i>et al.</i> ³³	1026.68 cm ⁻¹
23	P-O and P=O stretching vibrations of polyphosphates	880.92 cm ⁻¹ Werner <i>et al.</i> ³⁸	872.19 cm ⁻¹
Band distribution of Vermicompost (cm ⁻¹)			
24	O-H stretching of hydroxyl group of alcohols and phenols	3450 cm ⁻¹ Kumar <i>et al.</i> ³⁸	3852.20-3622.97 cm ⁻¹
25	C-H stretching	2927.85 and 2850.7 cm ⁻¹ García <i>et al.</i> ⁴⁰	2924.09 and 3272.60 cm ⁻¹
26	Phosphonates	2358-2360 cm ⁻¹ Kumar <i>et al.</i> ³⁸	2364.99 and 2314.67 cm ⁻¹
27	Quinones and amides	1649.09 cm ⁻¹ Fernández <i>et al.</i> ⁴²	1645.61 cm ⁻¹
28	C-O stretching of phenolic OH groups	1400 cm ⁻¹ Stevenson and Goh ⁴³	1401.47 cm ⁻¹
29	C=O stretching	1000 cm ⁻¹ Fong <i>et al.</i> ⁴⁴	1004.51 cm ⁻¹
30	Metal-Oxygen (M-O) interactions	603 cm ⁻¹ Kumar <i>et al.</i> ⁴⁵	685.83 cm ⁻¹

FT-IR analysis of Vermicompost

The FTIR spectra of vermicompost samples exhibited characteristic bands corresponding to functional groups of primary and secondary metabolites, highlighting the degradation and stabilization processes occurring during composting and vermicomposting (Table 1 & Fig. 6). The weak bands between 3852.20-3622.97 cm^{-1} may be attributed to O-H stretching vibrations of hydroxyl groups present in phenols and alcohols. The broad peaks at 2924.09 and 3272.60 cm^{-1} indicated C-H stretching vibrations of alkyl groups. The weak bands at 2364.99 and 2314.67 cm^{-1} may be identified as phosphonates. Furthermore, the band at 1645.61 cm^{-1} may be assigned to C=O stretching vibrations of quinones and amides. The band at 1401.47 cm^{-1} may be due to OH deformation and C-O stretching of phenolic OH groups, as well as C-H deformation. The FTIR analysis revealed distinct absorption bands corresponding to various functional groups. A peak at 1401.47 cm^{-1} was observed, which may be attributed to OH deformation and C-O stretching of phenolic OH groups, as well as C-H deformation of CH_2 and CH_3 groups. Another strong and broad band appeared at 1004.51 cm^{-1} , indicating the presence of significant alkene compounds or polymers, likely associated with C=O stretching vibrations. Additionally, a band at 685.83 cm^{-1} was detected, suggesting metal-oxygen (M-O) interactions.

Antifungal properties of OFs against *Curvularia lunata*

The OFs such as BA, JA, GJ, BS, DCDB, and VC were evaluated for their antifungal activity against *Curvularia lunata* by two methods (Table 2). In one set, all the aforesaid OFs were used directly and in

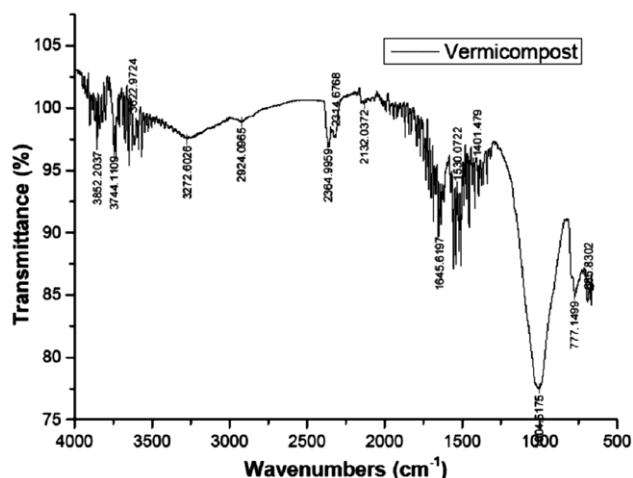


Fig. 6 — FT-IR interpretation of Vermicompost

another set, OFs were used after autoclaving. The purpose of performing experiment in two sets was to determine whether the antifungal activity was due to plethora of microorganisms present in the organic fertilizers or due to metabolites produced by various microorganisms. The maximum zone of inhibition (%) was observed in *Beejamrit* (70%) followed by desi cow dung bioenzyme (62.5%), *Jeevamrit* (57.5%), Biogas slurry (55%), Vermicompost (42.5%) and *Ghanjeevamrit* (37.5%) against *Curvularia lunata* when autoclaved OFs were used. Whereas, without autoclaving the OFs, the maximum zone of inhibition was reported in *Jeevamrit* (95%) followed by *Beejamrit* (55%) and desi cow dung bioenzyme (55%), Vermicompost (52.5%), Biogas slurry (40%) *Ghanjeevamrit* (37.5%) against *Curvularia lunata*.

Discussion

Beejamrit, *Jeevamrit* and desi cow dung bioenzyme

The spectra revealed distinct bands corresponding to various functional groups such as esters, thiols, hydroxyl, amide, alkene, alkyl halide, and Si-H linkages. The shared or overlapping spectral peaks observed across these OFs can be ascribed to their common parent compounds or constituents. Carbon-hydrogen (C-H) stretching vibrations are significant in FTIR spectroscopy because they provide critical information about the molecular structure and functional groups present in a compound¹¹. Similarly, Sivam *et al.*¹² reported a less intense band at 3625 cm^{-1} in the ethanol extract of cow dung, attributed to C-H stretching vibrations. The broad and strong bands at 3291.23, 3281.92, and 3280.05 cm^{-1} , related to O-H stretching, bring to agreement with findings by Rao¹³, who reported similar bands (3413-3421 cm^{-1}) suggestive of free N-H and O-H stretching vibrations in methanol and ethanol extracts of cow dung. The underlying role of the distribution of O-H bond lengths in broadening vibrational signals, particularly

Table 2 — Antifungal properties of OFs against *Curvularia lunata*

Organic Fertilizers	Percentage inhibition against pathogenic fungi (with autoclaving)	Percentage inhibition against pathogenic fungi (without autoclaving)
<i>Beejamrit</i>	70%	55%
<i>Jeevamrit</i>	57.5%	95%
<i>Ghanjeevamrit</i>	37.5%	37.5%
Biogas slurry	55%	40%
Desi cow dung bioenzyme	62.5%	55%
Vermicompost	42.5%	52.5%

in more distorted and less symmetric structures, has been established¹⁴. The critical role of hydroxyl groups in humic substances, as they facilitate plant growth by improving nutrient availability and influencing cell division and elongation, root growth, through hormonal signalling pathways such as auxins. The chelating properties of hydroxyl groups further improve micronutrient uptake, enhancing plant stress tolerance¹⁵. The combination of a hydroxyl group and a terminal double bond resulted in enhanced efficacy against mycobacteria¹⁶. The presence of thiol (-SH) groups, as suggested by the bands at 2323.99, 2357.54, and 2357.54 cm^{-1} , aligns with findings by Suresh *et al.*¹⁷, who found out a similar band 2524.62 cm^{-1} in the methanol extract of cow dung related to the S-H stretching vibration. Thiol groups possess significant role in redox signaling and metabolism led to improvement in growth of plants¹⁸. The compounds that contains thiols groups such as glutathione acts as antioxidants that regulates, sulphur species, nitrogen, reactive oxygen, promoting cell division, stress responses and offers root and shoot growth. Furthermore, thiol compounds can disrupt membrane integrity in association with bacterial enzymes that leads to cell death¹⁹. The presence of silicon-hydrogen (Si-H) stretching and boron based compounds was observed in the ethanol and methanol extracts of cow dung at 2130.07 and 2076.35 cm^{-1} minor bands²⁰. The C-H and Si-H stretching vibration serves their role as markers for surface transformations²¹. The functional derivatives of Si-H bond based compounds can be modified for antimicrobial effects, however Si-H bond itself does not show direct antimicrobial activity. For example, silicon-based materials functionalized with antimicrobial agents such silver nanoparticles or quaternary ammonium salts have demonstrated strong antimicrobial properties by disrupting microbial cells through ionic interactions or by releasing antimicrobial agents such as silver ions²². The presence of C=N stretching in amides at 1634.43, 1630.71, and 1641.89 cm^{-1} aligns with findings by Nautiyal and Dubey²³, who reported a band at 1636.1 cm^{-1} associated with C=N stretching in amides. The conformational structure of proteins and peptides can be obtained by the position and intensity of the peak²⁴. Additionally, alkamides influence rhizosphere microbial communities, promoting beneficial plant-microbe interactions that further improve nutrient availability, contributing to enhanced plant stress tolerance and growth²⁵.

The identification of C-C stretching vibrations of aromatic ring compounds at 1558.02, 1455.52, and 1455.52 cm^{-1} aligns with the findings of Anand and Suresh²⁶, who reported bands at 1452.11 and 1455.17 cm^{-1} due to similar vibrations. Additionally, the band at 1338.11 cm^{-1} in *Jeevamrit* and desi cow dung bioenzyme corresponds to the symmetrical and asymmetrical bending vibrations of the CH₃ (methyl) group. Similar bands at 1383.12 cm^{-1} and 1394.20 cm^{-1} , attributed to CH₃ (methyl) functional groups in the ethanol extract of cow dung²⁷. Methylation contributes to epigenetic regulation, modifying gene expression related to growth and defense responses, ultimately enhancing plant-microbe interactions and overall plant development²⁸. Carbon-based compounds demonstrate substantial growth inhibitory effects against various pathogenic microorganisms such as *Staphylococcus aureus* and *Pseudomonas fluorescens*, as well as yeasts like *Candida albicans* and filamentous fungi, specifically *Alternaria* and *Penicillium* species²⁹.

Biogas slurry

Cow dung is extensively utilized in biogas production, with the residual material repurposed as an organic fertilizer³⁰. The weak C-H stretching band in biogas slurry aligns with findings by Sivam *et al.*¹², who reported a similar less intense band at 3625 cm^{-1} in the ethanol extract of cow dung, attributed to C-H stretching vibrations. The strong O-H stretching band in biogas slurry at 3309.87 cm^{-1} corresponds with earlier findings by Rao¹³, who observed strong and broad bands within the 3413-3421 cm^{-1} range, indicative of free O-H and N-H stretching vibrations associated with hydroxyl and amino acid groups in ethanol and methanol extracts of cow dung. Additionally, Socrates²⁰, reported that small bands at 2076.35–2130.07 cm^{-1} observed in ethanol and methanol extracts of cow dung suggest the presence of silicon (Si-H stretching) and boron compounds. The presence of a peak at 1634.43 cm^{-1} in biogas slurry is indicative of C=O stretching vibrations of esters, aligning with findings by Yam *et al.*³¹, who observed a similar peak at 1759.41 cm^{-1} in ethanol extracts. The medium-intensity bands at 1634.43 cm^{-1} in carbonyl groups correspond to C=O stretching vibrations, with similar bands at 1632.84 cm^{-1} in ethanol and 1644.86 cm^{-1} in methanol extracts³². The detection of a band at 1455 cm^{-1} in biogas slurry, linked to C-C stretching in aromatic ring compounds, is consistent with Anand and Suresh²⁶ who reported a

similar band at 1460 cm^{-1} . The C–N stretching vibrations observed at 1338.11 cm^{-1} in biogas slurry align with findings by Li *et al.*³³, who reported a band at 1248.84 cm^{-1} , indicative of C–N stretching in amines. Amines play a crucial role in nitrogen metabolism and plant growth regulation.

Ghanjeevamrit

The C–H stretching vibrational band is typically well-separated within the vibrational spectrum and exhibits strong spectral intensity, making it highly suitable for identifying the hydrocarbon components of biological molecules³⁴. Similarly, Rao¹³, also stated that strong and broad bands centred at $3413\text{--}3421\text{ cm}^{-1}$ are attributed to free O–H and N–H stretching vibrations of hydroxyl and amino acid groups in ethanol and methanol extracts of cow dung. The occurrence of boron and silicon based compounds may strengthen its distinctive physical and chemical attributes as observed by Socrates²⁰. Yam *et al.*³¹ suggests the presence of bioactive ester compounds such as ester related to C=O stretching vibrations. Galactosyl myristate showed the maximum antibacterial activity against the *Salmonella typhimurium*, *Staphylococcus aureus*, *Bacillus subtilis*, among the evaluated ester compound. Whereas, glucosyl monomyristate showed maximum antibacterial activity against *E. coli*³⁵. The presence of amines, carbohydrates and polyphosphates was observed in *Ghanjeevamrit*. Further, the occurrence of carbonyl functional groups stipulates biologically active organic compounds and antimicrobial efficacy as observed by Stewart³². The C–N stretching vibrations may play pivotal role in microbial interaction because of the presence of nitrogenous compounds as observed by Stehfest *et al.*³⁶ Finally, the presence of polyphosphates containing bioactive compounds through the identification of polyphosphates may contribute to show antimicrobial effects as reported by Werner *et al.*³⁷.

Vermicompost

Vermicompost is an organic fertilizer produced through the decomposition of organic waste by earthworms. A broad band around 3450 cm^{-1} that also corresponds to O–H stretching of hydroxyl groups in alcohols and phenols³⁸. The antimicrobial properties of plant secondary metabolites are linked to the presence of hydroxyl (-OH) groups attached to the phenolic ring³⁹. The bands at 2927.85 and 2850.7 cm^{-1} , linking them to symmetric and asymmetric aliphatic CH stretching⁴⁰. Antimicrobial and antibiofilm activities against Gram-positive and Gram-negative

bacteria, as well as fungi, show a clear dependency on the length of the alkyl substituent. Additionally, 1-alkylquinolinium bromide ionic liquids exhibit strong antimicrobial effects against clinically significant pathogens, including methicillin-resistant *Staphylococcus epidermidis* (MRSE) and *Pseudomonas aeruginosa*⁴¹. Kumar *et al.*³⁸, reported weak bands in the $2358\text{--}2360\text{ cm}^{-1}$ range that were also attributed to phosphonates A band at 1649.09 cm^{-1} corresponding to the wide C=O but from amides and quinones⁴². The band at 1401.47 cm^{-1} is in agreement with the findings of Stevenson and Goh⁴³, who reported a peak at 1400 cm^{-1} associated with phenolic and alkyl functional groups. The presence of alkene compounds, inferred from the 1004.51 cm^{-1} band, is consistent with prior studies by Fong *et al.*⁴⁴, who identified similar peaks around 1000 cm^{-1} . The identification of M–O interactions suggests the possible role of metal complexes in OFs, as previously noted by Kumar *et al.*⁴⁵ These findings suggest a potential role of bioactive compounds in OFs, though existing literature on their identification remains limited. Further investigation is needed to establish the functional significance of these compounds in antifungal activity of CH₂ and CH₃ groups. A broad and strong band at 1004.51 cm^{-1} suggested the presence of significant alkene compounds or polymers, likely associated with C=O stretching vibrations, consistent with the peak at 1000 cm^{-1} shown by Fong *et al.*⁴⁴. Finally, the band at 685.83 cm^{-1} linked to metal-oxygen (M–O) interactions. However, limited and sparse literature is available on the identification of bioactive compounds in OFs.

Antifungal properties of organic fertilizers (OFs) against *Curvularia lunata*

In present study antifungal activity of OFs was studied against *Curvularia lunata* (Table 2). It is an important fungal pathogen responsible for Curvularia leaf spot in maize. The zone of inhibition of various OFs (non-autoclaved) ranged between 37.5% to 95%. Whereas, the zone of inhibition of autoclaved OFs ranged between 37.5% to 70%. The maximum antifungal activity was shown by *Beejamrit* i.e. 70% among autoclaved OFs, whereas *Jeevamrit* (95%) showed maximum antifungal activity from the non-autoclaved OFs. The possible reason for the presence of antifungal activity in the OFs (with autoclaving) may be great diversity of microorganisms and their metabolites. In the same way the possible reason of antifungal activity of autoclaved OFs may be heat stable metabolites produced by various microorganisms.

Conclusion

The current investigation elucidated the occurrence of a broad spectrum of functional groups in OFs. These functional groups may play a significant role in imparting bioactive properties to these organic fertilizers. The presence of these bioactive compounds not only enhances the efficacy of these formulations in promoting plant growth productivity and antifungal activity, but also offers their broader applications in sustainable agriculture and beyond. Furthermore, given their promising bioactive potential, these formulations could be explored in various other fields, such as pharmaceuticals, biomedicine, and environmental remediation.

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Author Contributions

Conceptualization of research work (GP); Execution of lab experiments; analysis of data and interpretation (NS, AK, ASS, AKC); Preparation of manuscript (NS, GP); Manuscript proofreading (GP), Supervision, Resources (AK, UGP). All authors read and approved the final manuscript.

Conflicts of Interest

Authors declare that there is no conflict of interest.

Ethical Approval

This study was conducted in accordance with relevant ethical guidelines to ensure the rights, dignity, and privacy of the participants.

Data Availability

All data supporting the findings of this study are included within the article. Additional data may be made available by the corresponding author upon reasonable request.

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