



Integrative Experimental and Bibliometric Study on the Antifungal Efficacy of Phytochemicals from *Chenopodium album* (Bathua) Seeds and Leaves in Reducing Fungal Growth in Bengal Gram under Field Conditions

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ABSTRACT

Background: *Chenopodium album* is a widely distributed weed native to Europe and Asia, thriving in subtropical, tropical and temperate climates. Owing to its broad occurrence and phytochemical richness, it has gained attention as a potential source of antifungal compounds. The present study investigates the antifungal potential of *Chenopodium album* extracts and emphasises the importance of identifying bioactive molecules to develop effective fungicides against fungal phytopathogens affecting Bengal gram crops.

Methods: Fresh leaf extracts of *Chenopodium album* were prepared using different organic solvents, including Methanol, Ethyl acetate, Butyl alcohol, Benzene and Water. The antifungal efficacy of these extracts was evaluated against *Fusarium oxysporum* infection through pot culture experiments on infected Bengal gram plants. Physiological alterations and disease symptoms were also assessed. Furthermore, GC-MS analysis was employed to identify the bioactive compounds responsible for antifungal activity. A bibliometric analysis based on the Scopus database was conducted to evaluate global research trends related to *Chenopodium album*.

Result: Among all tested extracts, the Benzene extract exhibited the highest antifungal activity against *Fusarium oxysporum*, significantly reducing fungal spores and disease severity in Bengal gram plants. The treatment also improved physiological parameters and reduced leaf yellowing symptoms associated with infection. GC-MS analysis confirmed the presence of bioactive phytochemicals responsible for suppressing fungal phytopathogens. Bibliometric findings revealed a steady global increase in publications on *Chenopodium album*, reflecting growing scientific interest in its antifungal properties and phytochemical applications.

Key words: Bibliometric analysis, *Chenopodium album*, GC-MS, Leaves, Phytochemicals, Pot experiment, Seeds.

INTRODUCTION

Since the beginning of agriculture, weeds have been a problem, as they are direct competitors of crops in water, nutrient and sunlight usage and reduce agricultural production (Monteiro 2022). One such weed that is ecologically and agronomically important is *Chenopodium album* L. The ten most widely spread plant species include the *Amaranthaceae* (Netland *et al.*, 2001). *C. album* is a widespread species in Europe and Asia, but can be successfully cultivated in subtropical, tropical and temperate regions worldwide and is one of the most cosmopolitan plants on Earth (Tang *et al.*, 2022). Chickpea (*Cicer arietinum* L.) is the most important leguminous crop around the world. Fusarium wilt incited by *Fusarium oxysporum* f. sp. ciceris is a major biotic constraint in chickpea production. The present investigation was undertaken to evaluate the efficacy of plant extracts, fungicides and bio-agents against *Fusarium oxysporum* f. sp. ciceris under *in vitro* and field conditions. Plant extracts and fungicides were evaluated using poison food technique while antagonistic activity of bio-agents was studied using dual culture technique under *in vitro* conditions. Field trials were conducted to evaluate the efficacy of different plant extracts, fungicides and bio-agents against Fusarium wilt at Experimental Area of Plant Pathology, CCS HAU, Hisar (Khanna *et al.*, 2024).

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It is intentionally grown as a leafy crop along with *rabi* crops like wheat, mustard and cereals in certain parts of India demonstrating its dual role as a weed and a useful ethnobotanical resource (Bhattacharjee 2001; Bajwa *et al.* 2019). Weed management during growing season has been a serious problem for many years. Worldwide, a 10% loss of agricultural products can be attributed to the competitive effect of weeds, despite their intensive control. *Dactyloctenium aegyptium* and *Chenopodium album* L. is an annual weed of cultivated fields (Sahrawat *et al.*, 2024).

The genus name *Chenopodium* comes from the Greek words *khén*, meaning 'goose' and *pous* meaning 'foot', as the leaves are shaped like a goose's foot (Singh *et al.*, 2023). *C. album* is tolerant to changing moisture content, pH and substrate temperature (Eslami *et al.*, 2021). It is considered a food and a medicinal herb in the tropical and subtropical Ayurvedic uses; it is still being studied for use as a nutraceutical all over the world (Gohar, 1997; Kirtikar and Basu, 1918). It has pharmacologic actions such as anthelmintic (anti-worm), anti-inflammatory, anti-rheumatic, anti-diarrheal, anti-oxidant and anti-microbial with the fruits used for burn treatment being reported with anaesthetic and cooling properties (Dkhar *et al.*, 2022). The special phytochemical profile of the plant also contains alkaloids, phenols, saponins, phytosterols, two important flavonoids, kaempferol and quercetin, essential oils and abundant potassium and albuminoids (Harrison, 2022). In recent years, a detailed review by (Majumdar *et al.*, 2025) brought together the pharmacological and nutritional evidence, which shows that all these bioactives together contribute towards the noted strong antioxidant, antifungal, anti-inflammatory and antibacterial properties of *C. album*, thus underscoring its therapeutic potential in contemporary research. Antifungal potential of leaves and roots parts of *Chenopodium album* was evaluated against five phytopathogenic fungi including *Alternaria alternata*, *Fusarium solani*, *Rhizoctonia solani*, *Pythium aphanidermatum* and *Sclerotinia sclerotium* using four concentrations *viz.* 0, 5, 10 and 15% of leaves and roots water extract led to significantly reduced of fungi mycelial growth. GC-MS analysis of leaves and roots water extract showed the presence of 7 compounds. 2(3H)-furanone, dihydro-4,4-dimethyl; 9-octadecenoic acid (Z), methyl ester; 9,12-octadecenoic acid (Z), methyl ester; 6-methylene bicyclo (3.2.0) hept-3-en-2-one., 1,2-benzene dicarboxylic acid, mono (2-ethylhexyl) ester and hexadecanoic acid, methyl ester. Five phytopathogenic fungi could be managed and controlled by the water leaves and roots extract of *C. album*. The antifungal activity of this extract was possible could be used to control a wide range of fungi (Alkooranee *et al.*, 2019). Quinoa (*Chenopodium quinoa* Willd.) and amaranth (*Amaranthus* spp.) are pseudocereals with potential as functional foods or raw materials for production of functional foods because of their high nutritional value and phenolic content. However, quinoa and amaranth are low consumed because of flours obtained from their native

grains do not have attractive flavor and their nutrients and phenolics have low bioavailability. Germination and roasted of quinoa and amaranth seeds are alternatives for improvement of flour characteristics. Germination and roasting did not affect the content of protein (10.49 to 11.80%), crude fiber (1.19 to 1.96%) and carbohydrates (72.76 to 74.77%), while moisture, ash and fat were affected resulting A-NG (5.23%), A-G (3.35%) and Q-G (6.98%) treatment with higher content, respectively. There was statistical difference in all color variables resulting with higher values A-NG in L^* (78.73) C^* (25.40) and h^* (73.77). Regarding to functional properties, in free extracts Q-G resulted with higher levels of total phenolics (6940 mg GAE/kg), condensed tannins (8064 mg CatE/kg) and ABTS (41005 μ mol TE/ kg), while A-G obtained higher levels in total flavonoids (1141 mg CatE/kg), DPPH (25351 μ mol TE/ kg) and FRAP (44327 μ mol TE/kg). Finally, in bound extracts the higher levels were for Q-G in total phenolics (412 mg GAE/kg) and FRAP (4869 μ mol TE/kg), A-NG in total flavonoids (263 mg CatE/kg), A-G in condensed tannins (584 mg CatE/kg), Q-NG in DPPH (1823 μ mol TE/kg) and ABTS (4869 μ mol TE/kg). The characteristics obtained from germinated and roasted quinoa and amaranth flours make them good ingredients for the development of pseudocereals based functional beverages in the near future (Rodríguez-Sánchez, 2026).

Research gap and justification

Soil-borne fungi pathogens are one of the greatest challenges in sustainable crop production. Although effective, synthetic fungicides are becoming less effective due to the emergence of resistance in pathogenic fungal strains and the environment and food safety concerns caused by their prolonged residency (Bhaik, 2022; Morea *et al.*, 2025). This has led to a worldwide trend towards botanical alternatives. The biofungicides derived from plants occupied about 33-38% of the global biofungicide market by 2024, where the global production of these biofungicides is estimated to be 450,000 tonnes, mainly neem-based biofungicides and essential oil products and other economic projections are expected to exceed USD 500 million by 2025. However, the systematic isolation and in addition, regulations regarding pesticide residues in an organic farming environment have increased the focus on the search for inexpensive and environmentally friendly plant-based fungicide alternatives that are available locally (Tzortzakis and Proestos, 2024). *C. album* possesses a demonstrated ability to resist diseases and environmental stresses that routinely afflict cultivated crops, making it a potentially rich source of anti-phytopathogenic compounds (Bhaik, 2022). Prior research has confirmed its antifungal potential: methanol extracts from leaves, stems, roots and inflorescences at concentrations of 0.5%-3.0% inhibited *Fusarium oxysporum* development by 24%-80%, with ethyl acetate sub-fractions achieving the highest activity (68%-100% biomass reduction) (Rauf 2013; Alkooranee *et al.* 2019). Against the highly destructive soil-borne pathogen

Sclerotium rolfsii, which infects over 500 plant species and reduces chickpea grain dry biomass by up to 50% compared to untreated controls—a 4% methanolic leaf extract caused up to 82% biomass reduction (Javaid *et al.*, 2020; 2023). GC-MS profiling of ethyl acetate and n-hexane sub-fractions from *C. album* leaves identified compounds including kitazin P and 9,12,15-octadecatrienoic acid, 2,3-dihydroxypropyl ester, which were postulated as key contributors to antifungal efficacy against *S. rolfsii* (Javaid *et al.*, 2023). More recently, a parallel approach using leaf extracts from *Argemone mexicana*, another weed species, confirmed via GC-MS that multiple solvent-polarity fractions yield structurally distinct antifungal compounds active against *F. oxysporum* and *Sclerotinia sclerotiorum*, underscoring the value of systematic multi-solvent GC-MS profiling across weed species.

Novelty of the present study

Although prior investigations have examined isolated fractions or single solvents, no comprehensive study has simultaneously: (i) evaluated multiple solvent extracts of *C. album* (methanol, ethyl acetate, butanol, benzene and aqueous) at graduated concentrations against Bengal gram (chickpea) fungal infection under pot-culture conditions; (ii) monitored the physiological modifications and infection indicators in the infected host plant in real time; and (iii) applied GC-MS profiling to systematically identify the bioactive compounds responsible for observed antifungal activity. This multi-pronged approach, which directly connects chemical fingerprinting to in planta disease outcomes, is novel and unique and will allow a bridge to be formed between in vitro bioassays and real crop protection. Furthermore, recent global reviews have documented the ever-increasing commercial potential of plant-derived fungicides (Majumdar *et al.*, 2025) and the use of a freely available weed species *C. album* as a source of phytofungicides with direct GC-MS validation represents an economically attractive and environmentally sustainable contribution to plant-based fungicide development. Gas Chromatography Mass Spectrometry (GC-MS) is now the benchmark technique for the profiling of secondary metabolites in a wide range of plant species and provides the finest resolution of volatile and semi-volatile bioactive constituents (Chak, 2021). In general, recent research has shown that the activity of plant extracts against fungi is often solvent-polarity dependent, as reported in similar studies with other plant extract systems (Morea *et al.*, 2025). The present study aims to: (i) evaluate the antifungal activity of methanol, ethyl acetate, butanol, benzene and aqueous extracts of *C. album* at varied concentrations against fungal contamination in pot-culture Bengal gram; (ii) assess the physiological changes and disease indicators in infected plants and (iii) characterize the bioactive compounds in active fractions through GC-MS analysis, thereby providing a scientifically grounded basis for the development of low-cost, plant-derived fungicides for sustainable chickpea crop protection.

MATERIALS AND METHODS

Study site and collection of plant material

Fresh, disease-free leaves of *Chenopodium album* L. were collected during the 2022-23 growing season from agricultural land adjacent to Sardar Vallabhbhai Patel Agriculture Technology College, Meerut, Uttar Pradesh, India (lat. 28.98° N, long. 77.71° E; elevation 237 m a.s.l.). Collection was carried out in the morning hours (07:00-09:00 h) to minimise post-harvest respiration losses. Bengal gram (*Cicer arietinum* L.) seeds, widely used in pathogenicity trials, were procured from the National Seeds Corporation outlet in Meerut.

Experimental design, treatment structure and replication

The pot-culture experiment was conducted as a completely randomised design (CRD) with five solvent extracts with three concentrations (5%, 10%, 15%) each replicated three times ($n = 3$), yielding 51 experimental units (pots) in total. This replication level is consistent with published pot-culture studies on *Fusarium* wilt management in chickpea (Chohan *et al.* 2024; Javaid *et al.* 2023). Pots were assigned positions using a random number table and redistributed weekly to account for positional effects under the open-air screenhouse environment. Preparation of *Chenopodium album* leaf extracts

Freshly collected leaves were washed three times with running tap water, followed by a final rinse with sterile distilled water to remove surface contaminants. Leaves were then spread on sterile muslin cloth and air-dried under shade at ambient temperature ($28 \pm 2^\circ\text{C}$) for 3-4 days until a constant weight was achieved (moisture content $< 8\%$, verified gravimetrically). Dried leaf material was ground to a fine powder in a Wiley mill and stored in airtight amber glass containers at 4°C until used for extraction. The extraction was done with a Soxhlet extraction apparatus with a ratio of 1:10 dried leaf powder to solvent. Soxhlet cycles were performed for 24 hours for each of the solvents in the following order of increasing polarity: benzene (non-polar)→ethyl acetate (moderately non-polar)→butanol/1-butanol (moderately polar)→methanol (polar)→water (highly polar). The sequential extraction technique reduces cross-contamination between fractions and provides sequential coverage of the entire polarity spectrum (Rauf 2013; Javaid *et al.*, 2023). Both crude extracts were filtered through Whatman No. 1 filter paper and then concentrated to dryness under reduced pressure at 40°C on a rotary evaporator (Buchi R-100, Switzerland). Dry residues were weighed and the percentage yield (w/w) was calculated. Solutions were prepared at 100 mg/mL in the original solvent (1% DMSO used as co-solvent for less soluble fractions as needed). Five, ten and fifteen percent (v/v) working concentrations were prepared by serial dilution with sterile distilled water just prior to use.

Isolation, identification and culturing of fungal pathogens

The affected plants of Bengal gram showing typical wilt, collar rot and root rot symptoms were collected from

farmers' fields in Meerut district. Root, stem and leaf pieces of infected plants were sequentially placed in 70% ethanol (30 s), 1% sodium hypochlorite (2 min) and 3 rinses in sterile distilled water for surface sterilisation. Segments (5 mm) were plated onto potato dextrose agar (PDA) (HiMedia, India) and incubated at $28 \pm 1^\circ\text{C}$ for 5-7 days. Emerging fungal colonies were sub-cultured repeatedly to obtain pure cultures. Three target pathogens were identified based on colony morphology, microscopic hyphal and spore characteristics and comparison with standard published mycological keys: *Fusarium oxysporum* f. sp. *ciceris*, *Rhizoctonia solani* (AG-4) and *Sclerotium rolfsii*. Pathogenicity was confirmed by satisfying Koch's postulates on susceptible Bengal gram seedlings (cv. Pusa 256) following the protocol (Srinivas *et al.* 2024). Re-isolated cultures were stored as glycerol stocks (15% v/v glycerol at 80°C) and as PDA slants at 4°C for use throughout the study. Inoculum for pot trials was prepared as follows: grain-based inoculum was produced by growing each pathogen on autoclaved sorghum grains (121°C , 15 min $\times$ 3 cycles on consecutive days) inoculated with mycelial discs (5 mm) and incubated at 28°C for 14 days. The fully colonised grain was air-dried, ground and the inoculum density was adjusted to 1×10^6 colony-forming units (CFU) g^{-1} of soil using dilution plating on PDA, following the methodology described by Chohan *et al.* (2024).

Pot culture establishment and pathogen inoculation

Uniform earthen pots were filled with 1.5 kg of autoclaved (121°C , 1 h) sandy-loam soil. Soil texture and pH were selected to support optimal *F. oxysporum* f. sp. *ciceris* growth consistent with published guidelines (Chohan *et al.*, 2024). Each pot received 10 g of grain-based inoculum of the mixed pathogen consortium (*F. oxysporum*, *R. solani* and *S. rolfsii*) mixed thoroughly into the top 5 cm of soil 7 days before sowing to allow pathogen establishment (positive control and treated pots only). Negative control pots received autoclaved uninoculated sorghum grain.

Extract application

At 3 days after sowing (DAS), each pot in the treated group was drenched with 100 mL of the respective extract solution (5%, 10%, or 15% v/v) per pot. Applications were repeated at 7-day intervals for a total of four applications (3, 10, 17 and 24) to maintain sustained antifungal pressure throughout the critical seedling establishment period. Control pots were drenched with equivalent volumes of sterile distilled water.

Statistical analysis

All data were subjected to one-way Analysis of Variance (ANOVA). F-test was significant ($p < 0.05$), Tukey's honest significant difference (HSD) post-hoc test was applied at the 5% level of significance to separate treatment means. Data expressed as percentages (DI%, DSI) were arcsine square-root transformed before ANOVA to stabilise variance. Results are presented as mean $\pm$ standard error (SE) of three replicates.

GC-MS analysis of chenopodium album leaf extracts

The most biologically active extract fraction (as determined by the lowest disease incidence in pot trials) was selected for detailed GC-MS characterisation. Analysis was performed on an Agilent Technologies 7890A GC coupled with a 5975C MSD detector, equipped with a HP-5MS capillary column (30 m $\times$ 0.25 mm i.d., film thickness 0.25 μm). Helium (purity $\geq 99.999\%$) was used as carrier gas at a constant flow rate of 1.0 mL min^{-1} . The injector temperature was 250°C ; sample injection volume was 1 μL in split mode (split ratio 10:1). The oven temperature programme was: initial hold at 60°C for 2 min, ramp at $10^\circ\text{C min}^{-1}$ to 300°C , final hold for 10 min. Ion source temperature was 230°C ; interface temperature 280°C . Electron ionisation (EI) was applied at 70 eV; scan range m/z 50-600. The mass spectra of the compounds detected in the GC-MS analysis were compared with the NIST 2020 Mass Spectral Library (NIST20) and compounds were identified based on their spectral matching with reference spectra (match quality threshold $\geq 85\%$). Relative percentage composition of each compound was calculated from the Total Ion Chromatogram (TIC) peak area, without correction factors. Compounds with a TIC peak area $< 0.01\%$ were considered trace-level and excluded from quantitative interpretation. All GC-MS analyses were performed in triplicate on independently prepared extract solutions to confirm reproducibility (Ali, 2017).

RESULTS AND DISCUSSION

C. album extract change promoted germination and physiological function of fungal plant pathogens *Fusarium oxysporum*, *Rhizoctonia solani* and *Sclerotium rolfsii* are pathogens responsible for various diseases in Bengal gram, affecting the leaf, stem and root. and decreased sickness signs, specifically at higher concentrations in pots. however, most of these barriers had been located to apply from low to high tiers (5%, 10% and 15%). Information is given in Table 1 and 2. The extract showed the best effect against *Fusarium oxysporum* causing leaf diseases and yellowing of Bengal gram leaves however, the extract reduced *Fusarium* spores. The extract has been shown to have beneficial effects on the physiology and symptoms of the Bengal gram plant. The phytochemical profile of the extract of *Chenopodium album* leaf (S5W1L) was complex as identified by Gas Chromatography - Mass Spectrometry (GC-MS) analysis, with both volatile and semi-volatile phytochemicals. Each peak in the chromatogram had different retention times suggesting that various groups of chemicals such as alkanes, alkenes, esters, aldehydes and oxygenated chemicals were present (Kumar, 2018).

The most abundant compound identified was 1,5-Hexadiyne (50.94%), followed by Bicyclo (3.2.0) hept-2-en-6-one, 7-chloro- (25.10%) and 1,3-Butadiene, 2-(chloroethenyl)- (9.94%). These are significant constituents of the extract's chemical makeup and could be the cause of biological properties. The minor compounds present in

C. album-Phytol (0.19%), 2-Pentadecanone, 6,10,14-trimethyl- (0.06%) and Hexadecanoic acid derivatives are known to have antioxidant, antimicrobial and anti-inflammatory activity, which have supported the ethnomedicinal use of *C. album*. The extract contains a variety of biochemical diversity, indicated by the presence of halogenated hydrocarbons, oxygenated ketones and long-chain fatty acid derivatives. A few trace compounds, such as dibutyl phthalate and toluene, were probably present as residues of solvents or contamination from laboratory processes or equipment and were not included in bioactivity interpretation. The detailed data are given in Table 3. Considering the retention times, the presence of the major components in the ginseng leaf extract was confirmed through the GC-MS spectral profile. The chromatogram displayed 30 distinct peaks, of which six compounds exhibited notable antifungal activity. Several unidentified compounds were also detected (Verma 2020). The detected compounds were identified by comparing their mass spectra with reference spectra in the NIST 2020 Mass Spectral Library (NIST20), supported by literature reports on fragmentation patterns, molecular ions and retention times (Manohar and Sankar, 2011). The major peaks were observed at retention times of 4.54, 4.75, 5.59, 6.56, 29.468 and 34.927 minutes. The corresponding compounds were identified as Norbornane (C_7H_{12} , MW 96), Toluene (C_7H_8 , MW 92), Acetic acid butyl ester ($C_6H_{12}O_2$, MW 116), Ethylbenzene (C_8H_{10} , MW 106), Phytol ($C_{20}H_{40}O$, MW 296) and Hexadecanoic acid ($C_{16}H_{32}O_2$, MW 256). In addition, a higher molecular weight compound, 2-Hydroxy-1-(hydroxymethylphenyl)-2-hydroxy-1- ($C_{36}H_{70}O_2$, MW 534), were also identified in Fig 1. The structural identification of these compounds was further confirmed by analyzing their ion mass and fragmentation patterns, which were consistent with literature data and NIST library spectra.

UV-visible spectrophotometric analysis of *Chenopodium album* leaf extract

The UV-Visible spectral analysis of the *Chenopodium album* leaf extract dissolved in benzene was conducted to identify the presence of conjugated biomolecules and to evaluate electronic transitions associated with phytochemical constituents. The absorption spectrum recorded within the wavelength range of 200-650 nm (Fig 2) exhibited a prominent absorption peak at approximately 300 nm, followed by a gradual decline in absorbance towards the visible region, as shown in Fig 3. The strong absorption band near 300 nm corresponds to the $\pi \rightarrow \pi^*$ electronic transition, which is characteristic of compounds containing conjugated double bonds and aromatic systems, such as flavonoids, phenolic compounds and alkaloids (Kumar, 2018; Verma, 2020; Saxena, 2017). The presence of these chromophores indicates that the extract contains polyphenolic structures capable of donating electrons, reflecting their potential antioxidant properties. The gradual decrease in absorbance beyond 350 nm indicates the absence of significant $n \rightarrow \pi^*$ transitions typically associated with non-conjugated carbonyl groups. This suggests that most of the active compounds present in the extract are conjugated or aromatic in nature. The relatively high absorbance intensity in the UV region also indicates that benzene acted as an effective solvent for extracting non-polar phytoconstituents. Overall, the UV-Visible spectral profile confirms the presence of major bioactive compounds, including phenolics, flavonoids and other aromatic compounds, which may contribute to the observed antimicrobial and antioxidant potential of *Chenopodium album* leaf extract. These findings are consistent with previous reports highlighting the presence of UV-active phenolic constituents in *Chenopodium* species.

Table 1: *Chenopodium album* leaves extracts (mg/ml) effects of physiological changes in Bengal gram.

Solvent	Germination (%) Mean $\pm$ SD ($\pm$ SE)	Mean Inhibition (<i>F. oxysporum</i>)	Mean Inhibition (<i>R. solani</i>)	Mean Inhibition (<i>S. rolfsii</i>)	Overall mean inhibition
Methanol	65.0 $\pm$ 12.91(SE 6.45)a	1.25	1	0.5	0.9
Ethyl acetate	72.5 $\pm$ 9.57(SE 4.79)a	0.75	2.25	0.75	1.25
Butyl alcohol	67.5 $\pm$ 17.08(SE 8.54)a	1.75	1	0.75	1.17
Benzene	77.5 $\pm$ 9.57(SE 4.79)a	0.25	1.25	1.75	1.08
Water	67.5 $\pm$ 9.57(SE 4.79)a	1.25	1.25	1.25	1.25

Table 2: Disease symptoms in Bengal gram crops were observed after treatment with *Chenopodium album* leaf extracts to evaluate their effectiveness.

Solvent	Mean (<i>F. oxysporum</i>)	Mean (<i>R. solani</i>)	Mean (<i>S. rolfsii</i>)	Overall mean
Methanol (S3W1L)	2.25	0.75	0.75	1.25
Ethyl acetate (S4W1L)	1.25	2.25	1.25	1.58
Butyl alcohol (S1W1L)	2.00	1.25	1.25	1.50
Benzene (S5W1L)	0.75	1.50	2.25	1.50
Water (S2W1L)	1.50	1.50	1.50	1.50

Bibliometric analysis

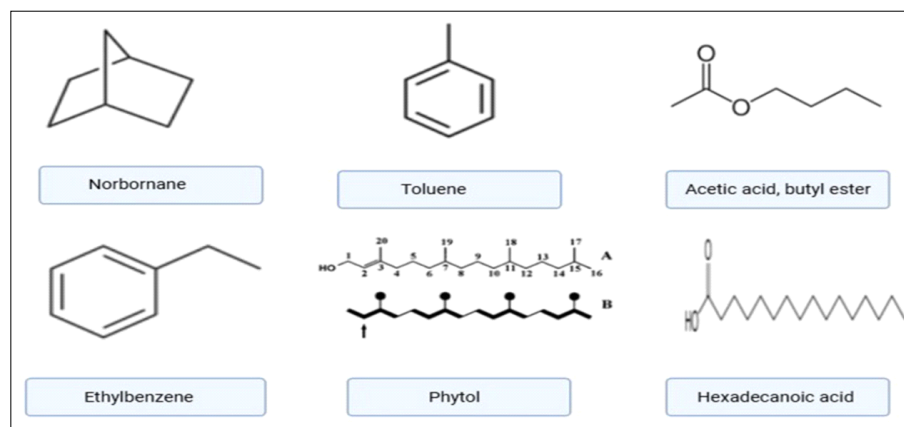
The methodological premise of the bibliometric component is provided through Fig 3, which records the systematic retrieval and screening procedure of the study. The PRISMA-style diagram reports the preliminary search

(n=1,399), consecutive search with the inclusion criteria.

This open process makes the work reproducible and provides the context of all the quantitative outputs. Fig 4 measures the temporal inertia of the field: the histogram of the number of publications annually shows that there

Table 3: Bioactive analysis of S5W1L by GC-MS.

Peak no	Retention time (in minutes)	% of probability	Name of bioactive compound
1	2.746	2.80	1,5-Hexadiyne
2	2.828	6.26	1,3-Butadiene, 2-(chloroethyl)-
3	3.187	25.10	Bicyclo[3.2.0]hept-2-en-6-one, 7-chloro-
4	3.302	9.94	1,3-Butadiene, 2-(chloroethyl)-
5	3.796	50.94	1,5-Hexadiyne
6	4.199	1.43	Cyclohexane, methyl-
7	4.307	0.64	Cyclopentane, ethyl
8	4.543	0.79	Norbornane
9	4.753	1.26	Toluene
10	5.596	0.08	Acetic acid, butyl ester
11	6.569	0.23	Ethylbenzene
12	6.766	0.12	Benzene, 1,3-dimethyl-
13	7.274	0.03	Benzene, 1,3-dimethyl-
14	12.454	0.01	Benzene, 1,2,4,5-tetramethyl-
15	12.533	0.01	Benzene, 1,2,4,5-tetramethyl-
16	20.731	0.01	2(4H)-Benzofuranone, 5,6,7,7a-tetrahydro-4,
17	24.628	0.01	6-Hydroxy-4,4,7a-trimethyl-5,6,7,7a-tetrahy
18	24.884	0.01	2-Cyclohexen-1-one, 4-hydroxy-3,5,5-trimet
19	25.683	0.06	2-Pentadecanone, 6,10,14-trimethyl-
20	26.830	0.01	7-Hexadecenal, (Z)-
21	27.336	0.01	Dibutyl phthalate
22	27.906	0.01	1-Decanol, 2-octyl-
23	29.315	0.01	cis-4,10,13,16-Docosatetraenoic Acid methyl
24	29.468	0.19	Phytol
25	29.760	0.01	1-Isobutylsulfanylmethyl-2,8,9-trioxa-5-aza-
26	30.790	0.01	2-Hexadecen-1-ol, 3,7,11,15-tetramethyl-, ac
27	32.287	0.01	6-Bromohexanoic acid, 5-ethyl-3-octyl ester
28	32.505	0.01	4,8,12,16-Tetramethylheptadecan-4-olide
29	34.595	0.01	1H-Indene, 1-hexadecyl-2,3-dihydro-
30	34.927	0.01	Hexadecanoic acid, 2-hydroxy-1-(hydroxym

**Fig 1:** The individual compounds identified based on their retention times.

has been a steady trend of increases in the last five-year period, with a sharp uphill slope, attesting to the rising interest of the scientific community in plant-derived antifungals and methods of their analysis, such as GC-MS. To provide a context for changes in the area of interest in terms of research investment and technology adoption, Fig 4 fills this in by plotting cumulative scientific production

and identifying the inflexion years in which production rises significantly (Aria, 2017). The contribution in terms of geography is also summarised in Fig 4 and corresponding author countries in Fig 5. Importantly, Fig 6 (RPYS) detects landmark publication years corresponding to seminal methodological developments or influential reviews; peaks in RPYS guide interpretation of why certain concepts gained

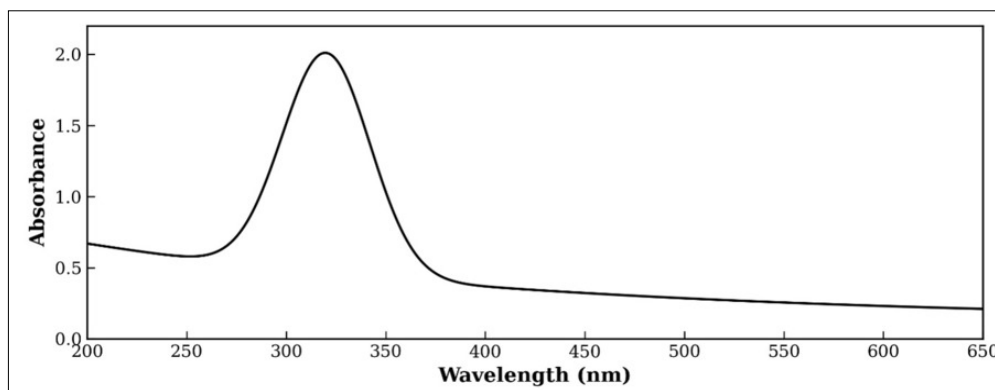


Fig 2: UV-Visible spectrophotometer of *Chenopodium album* leaf extract in Benzene.

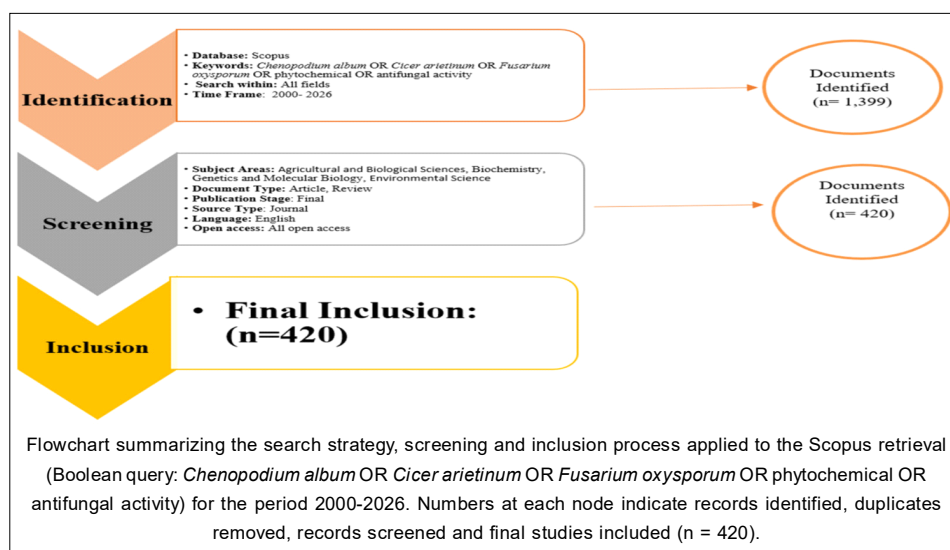


Fig 3: PRISMA-style flow diagram.

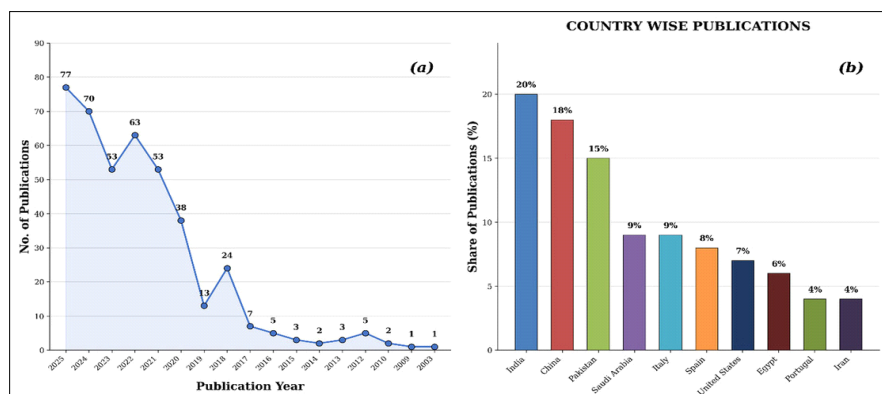


Fig 4: Annual and country-wise trends in chenopodium album antifungal research.

traction at specific points in time. The co-occurrence network (Fig 7) clusters keywords into thematically coherent groups; for example, extraction solvents and GC-MS sit with phytochemical identification; antifungal efficacy and crop metrics form another cluster indicating how methodological and application threads interweave (Donthu, 2021).

Environmental, agricultural and policy implications

The implications of this study are environmental, agricultural and policy implications of the findings. Traditional chemical fungicides, though effective, create a problem of soil degradation, microbial imbalance and food crop residual contamination, which are dangerous to both human and ecosystem health. Conversely, by revealing its antifungal activity, the *Chenopodium album* provides a renewable and biodegradable solution that is in line with the international focus of decreasing the use of synthetic pesticides. This is because of its accessibility, low costs and environmental friendliness due to its popularity as a

widely used weed by rural and small-scale farmers. Application of plant-derived antifungal agents, including *C. album*, in crop protection strategies could improve soil fertility, safeguard soil organisms and boost agricultural biodiversity while being environmentally safe. In policy and research terms, the presented bibliometric analysis of the literature in this study indicates the continuously increasing attention on plant-based antifungal agents and green tools of crop protection in the world. The interdisciplinary programs between plant biochemistry, pathology and environmental biotechnology should be encouraged by governments, academic institutions and funding bodies to come up with standardised, phytochemical-based formulations of biocontrol. The development of *C. album* as a controlled, cultivated and industrialised commodity may now convert an invasive weed into a useful bioresource. Moreover, scientific visibility and innovation in this area will be improved by encouraging the open-access distribution of data and global research partnerships that will be engaged with the help of bibliometric networks.

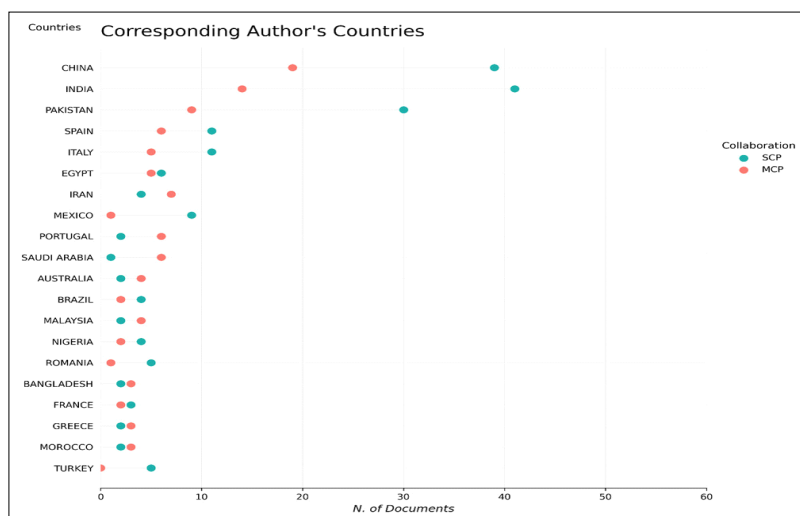


Fig 5: Most relevant countries. Ranked chart of countries by normalised output (publications per million researchers or adjusted for GDP), emphasizing relative productivity beyond absolute counts.

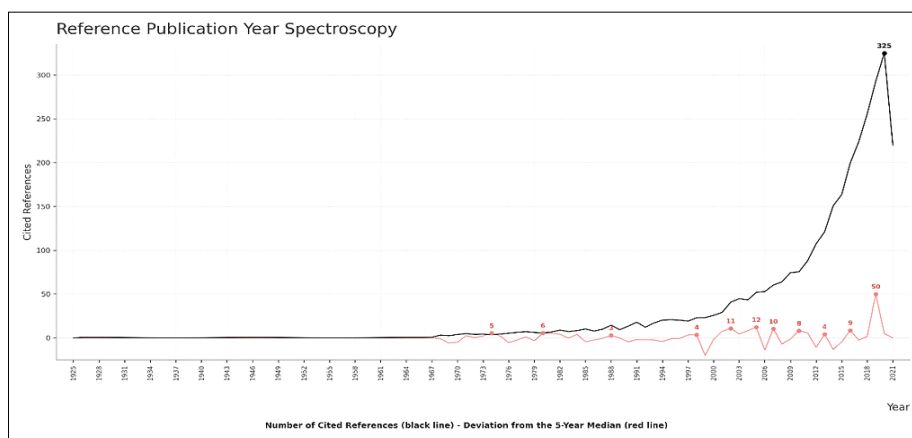


Fig 6: Reference publication year spectroscopy. RPYS plot indicating citation frequency peaks by reference publication year; annotated peaks identify landmark years and foundational publications that shaped research directions.

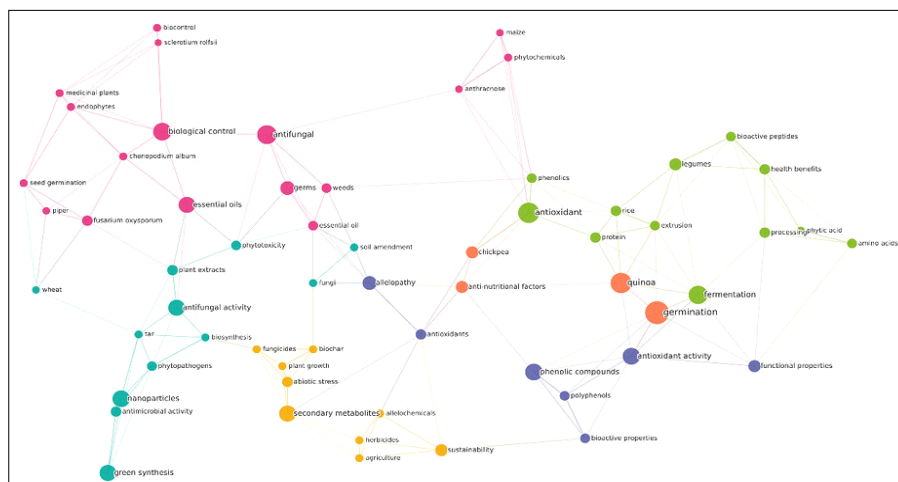


Fig 7: Co-occurrence network. Keyword co-occurrence visualization mapping major thematic clusters (e.g., phytochemicals, antifungal activity, GC-MS, crop protection) and their interrelationships.

The policymakers need to encourage industries to use green extraction technologies and biodegradable formulations made using native biodiversity plants, develop sustainable crops and strengthen the global responsibility towards the United Nations Sustainable Development Goals (SDGs 2: Zero Hunger, 12: Responsible Consumption and Production and 15: Life on Land). To provide a context for changes in the area of interest in terms of research investment and technology adoption, Fig 4 fills this in by plotting cumulative scientific production and identifying the inflexion years in which production rises significantly. The contribution in terms of geography is also summarised in Fig 4.

CONCLUSION

At concentrations of 10% and 15%, the *Chenopodium* extract showed a significant enhancement in leaf area, root length and stem elongation compared to the control. Additionally, the rate of decontamination of fungal spores was markedly improved at these concentrations, indicating the antifungal potential of the extract. The present study provides a comprehensive phytochemical and spectral evaluation of the *Chenopodium album* leaf extract, highlighting its significant potential as a source of bioactive compounds. The UV-Visible spectrophotometric analysis revealed a strong absorption peak around 300 nm, indicative of $\pi \rightarrow \pi^*$ electronic transitions associated with conjugated aromatic systems such as flavonoids, phenolics and alkaloids. These findings confirm the presence of chromophoric compounds with potential antioxidant activity. Further, the GC-MS analysis of the benzene extract identified several key phytoconstituents, including Indole, Vitamin E, Nonanoic acid, Benzyl alcohol and Dodecanoic acid, among others. Many of these compounds are known for their antifungal, antimicrobial and antioxidant properties, supporting the traditional medicinal use of *Chenopodium*.

album. A significant number of the detected compounds have been reported to possess antifungal, antimicrobial and antioxidant effects, which justifies the age-old medicinal role and usage of *Chenopodium album*. The joint experimental and bibliometric results thus support the classification of *C. album* as an efficient candidate to design the environmentally friendly fungicidal agents and highlight the need to investigate further its bioactive molecules in the field, prerequisites to implement the same in extensive agricultural applications.

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Disclaimers

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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