



RESEARCH ARTICLE

Management of sorghum rust caused by *Puccinia purpurea* Cooke by employing an integrated approach

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Abstract

Sorghum (*Sorghum bicolor* L.) is an important cereal crop grown in semi-arid, subtropical, tropical and temperate regions and it ranks fifth in worldwide cereal crop production. Rust of sorghum (*Puccinia purpurea* Cooke) is an important emerging disease in most sorghum growing areas of the world, which can increase susceptibility to other pathogens. Thus, there is a need to focus more on managing the disease. An attempt was made to manage the disease by integrating effective fungicides, botanicals, indigenous technical knowledge (ITKs) and bioagents under *in vitro* and *in vivo* conditions. *In vitro* studies revealed that among the different fungicides, botanicals, ITKs and bioagents tested, tebuconazole 50 % + trifloxystrobin 25 % and hexaconazole 5 % EC recorded 100 % uredospore germination inhibition. Among the botanicals, turmeric extract at 25 %, neem extracts at 50 % (78.39 %) while panchagavya (52.07 %) and combination of *Trichoderma harzianum* (5 g/L) and *Pseudomonas fluorescens* (5 g/L) (82.91 %) which recorded highest mean per cent inhibition of uredospore germination irrespective of concentration tested. Among 11 integrated spray schedules evaluated in a field study at the Main Agricultural Research Station (MARS), Dharwad during rabi seasons of 2021 and 2022, tebuconazole 50 % + trifloxystrobin 25 % at 0.05 % was significantly superior spray schedule. It recorded the lowest per cent disease index (PDI) of about 16.01 with highest grain yield (16.25 q/ha) and cost-benefit ratio (B:C ratio) of 1.87 followed by hexaconazole 5 % EC at 0.1 % (18.84 PDI; 15.76 q/ha). However, the highest PDI (92.50), lowest grain yield (9.63 q/ha) and B:C ratio (1.17) was recorded in the unsprayed control. The findings of this study highlight the potential of integrated disease management approaches combining chemical, biological and botanical components to achieve sustainable and economically viable control of sorghum rust and enhance productivity under semi-arid agro-ecological conditions.

Keywords: *in vitro*; panchgavya; PDI; rust; sorghum; uredospore

Introduction

Sorghum (*Sorghum bicolor* (L.) Moench), a member of the Poaceae family, is the fifth most important cereal crop globally in terms of area and production (1). Among the 22 species within the genus Sorghum, *S. bicolor* is the primary contributor to cultivated sorghums, displaying significant variability. Sorghum's global cultivation varies by region; it serves primarily as animal feed in the United States, Australia and South America, while being a key food source in Africa and India, particularly in semi-arid regions prone to stress (2). In India, rainy-season sorghum is mostly used as feed due to quality deterioration from harvest-time rains. In contrast, post-rainy season sorghum, known for its superior grain quality, is primarily consumed as food. Additionally, sorghum is a critical fodder source during dry seasons, contributing to food security (3). Globally, the top sorghum producers are the USA, Sudan, Mexico, Nigeria and India, contribute 77 % of world production, with India ranking sixth in production. During 2024–25, global sorghum production was approximately 62.98 Mt from 40.90 Mha, with a productivity of 1540 kg/ha (4). In India, sorghum is cultivated on 4.80 Mha, yielding 4.8 Mt with productivity of 1250 kg/ha, predominantly

in Maharashtra and Karnataka, which together account for 58.24 % of the country's production (4). Karnataka, the second-largest producer after Maharashtra, relies heavily on sorghum, with 50 % of its population depending on it as a staple food crop, cultivating 7.33 lakh hectares and producing 7.70 lakh tonnes with a productivity of 996 kg/ha (5).

Sorghum rust caused by *Puccinia purpurea* Cooke, is an increasingly significant disease in sorghum-growing regions worldwide, predisposing plants to other major diseases such as Fusarium stalk rot, charcoal rot and grain mould (6). Colonel Hobson first identified the disease in India between 1870 and 1876. The disease was observed in various parts of the world including Philippines, Africa, Italy, Greece, Portugal, Java and North and South America. The pathogen, native to eastern Australia, was first described by Cooke in 1876 and has since become widespread across temperate and tropical areas and its first report was in Kansas City, USA in 1927 (7, 8). Today, *P. purpurea* is prevalent across all continents, including Asia, Africa, the Americas, Madagascar, Australia, Europe and Oceania (9). Despite its wide distribution, there are limited reports on effective management strategies for this

disease under field conditions. This highlights the need for comprehensive investigations to identify and recommend the most effective fungicide formulations for use in farmer's fields. Additionally, there is a lack of information on the bio-efficacy of biocontrol agents and botanicals that could be incorporated into integrated disease management practices. In light of these challenges, the present study aims to develop an integrated management strategy for the control of sorghum rust.

Materials and Methods

Soil and climatic conditions

The experiments were conducted at the University of Agricultural Sciences (UAS), Dharwad, Karnataka, situated in the northern transition zone of the state in two seasons on 24 October 2021 during rabi 2021 and 16 November 2022 during rabi 2022. The experimental fields are characterized by black cotton soils (vertisols), which are deep, clayey soils with high montmorillonite clay content and pronounced swelling and shrinking behavior. These soils are typically neutral to slightly alkaline in reaction (pH ~6.7–8.8), non-saline (EC ~0.16–0.67 dS m⁻¹), low to medium in organic carbon (approximately 0.15–1.16 %) and often calcareous, containing appreciable amounts of free calcium carbonate. Such vertisols are widely distributed on the Dharwad (10). The region experiences a semi-arid tropical monsoon climate, with the bulk of rainfall received during the southwest monsoon period (June–September). The long-term mean annual rainfall of the Dharwad region ranges between 740 and 750 mm, with July being the wettest month alongside considerable inter-annual variability. Mean maximum temperatures during summer range from 36–37 °C, while minimum temperatures during winter may drop to around 14 °C; relative humidity generally varies between 42 % and 86 % depending on the season (11).

Cavity slide method

The cavity slide method is an *in vitro* technique commonly used to study spore germination and to evaluate the effect of fungicides, botanicals, bioagents, or other treatments on fungal pathogens. In this method, clean and sterilised cavity slides and cover slips are used. A drop of the test solution at the required concentration is placed in the cavity of the slide and freshly collected spores of the pathogen are added aseptically. The cavity is then gently covered with a sterile cover slip to avoid air bubbles. The prepared slides are kept in a moist chamber, usually a petri plate lined with moist blotting paper, to maintain high humidity and are incubated at an optimum temperature, generally around 25 ± 1 °C. After a specified incubation period, the slides are observed under a compound microscope to record spore germination and germ tube development (12). The percentage of spore germination and inhibition over control is calculated and the data are subjected to statistical analysis, commonly following a completely randomised design (CRD).

In vitro evaluation of fungicides against *Puccinia purpurea*

Four contact fungicides-chlorothalonil (Kavach 75 % WP), mancozeb (Indofil M-45 75 % WP), propineb (Antracol 70 % WP) and zineb (Zineb 75 % WP) were evaluated at concentrations of 0.1 %, 0.2 % and 0.25 %. Additionally, six systemic fungicides-propiconazole (Tilt 25 % EC), hexaconazole (Contaf 5 % EC), tebuconazole (Folicur 25.9 % EC), difenoconazole (Score 25 % EC), pyraclostrobin (Header 20 % WG) and validamycin (Sheathmar 3 % L) were tested at 0.025 %, 0.05 % and 0.10 % concentrations. Six combi-product-tebuconazole

50 % + trifloxystrobin 25 % (Nativo 75 % WG), metiram 55 % + pyraclostrobin 5 % (Cabrio Top 60 % WG), hexaconazole 5 % + captan 70 % (Taqat 75 % WP), tricyclazole 18 % + mancozeb 62 % (Merger 80 % WP), carbendazim 12 % + mancozeb 63 % (Saaf 75 % WP) and azoxystrobin 25 % + difenoconazole 12.5 % (Amistar Top 37.5 SC) were evaluated at 0.05 %, 0.1 % and 0.2 % concentrations. The study was conducted under *in vitro* conditions using the cavity slide method (12). Germination of uredospore was calculated using the formula given below and per cent inhibition of uredospore germination was calculated (13). A CRD was followed, maintaining 4 replications for contact fungicides and 3 replications for systemic and combi-product fungicides.

In vitro evaluation of commercially available botanicals against *Puccinia purpurea*

Different commercially available botanicals [Nimbecidine (azadirachtin 0.03 %), Vijayneem (azadirachtin 0.03 %), Kaneem (azadirachtin 0.03 %), Neemazal (azadirachtin 1 %), Elixer (turmeric extract 25 %, neem extract 50 %) and Shefaneem (azadirachtin 0.15 %)] were evaluated at 0.25 %, 0.50 % and 1.0 % concentrations in 3 replications under *in vitro* conditions using the cavity slide method (12). Germination of uredospore was calculated by the formula below and per cent inhibition of uredospore germination was determined (13).

In vitro evaluation of bioagents against *Puccinia purpurea*

The bio-efficacy of three bioagents: *Trichoderma harzianum* Rifai, *Pseudomonas fluorescens* Migula and *Bacillus subtilis* Cohn collected from the Institute of Organic Farming (IOF), UAS, Dharwad was evaluated both individually and in combinations under *in vitro* conditions using the cavity slide method (12). The bioagents tested included T1: *T. harzianum* (10 g/L), T2: *P. fluorescens* (10 g/L), T3: *B. subtilis* (10 g/L), T4: *T. harzianum* + *P. fluorescens* (5 g/L each), T5: *T. harzianum* + *B. subtilis* (5 g/L each), T6: *B. subtilis* + *P. fluorescens* (5 g/L each) and T7: *T. harzianum* + *P. fluorescens* + *B. subtilis* (3.3 g/L each) with 3 replications. Germination of uredospore was calculated by the formula given below and per cent inhibition of uredospore germination was calculated (13).

In vitro evaluation of indigenous technical knowledge (ITKs) against *Puccinia purpurea*

Panchagavya (materials required: desi cow dung: 350 g, ghee: 50 g, cow urine: 500 mL, cow milk: 150 mL, curd: 100 mL, jaggery: 150 g and water: 500 mL per litre of preparation) and vermiwash were collected from the biofarming unit, IOF, UAS, Dharwad and jeevamruta (materials required desi cow dung: 50 g, cow urine: 50 mL, gram flour: 5 g, soil: a handful of soil from the farm bund, jaggery: 5 g and water: 1000 mL per litre of preparation), buttermilk and cow urine from the natural farming unit, UAS, Dharwad. These ITKs were evaluated at 5 %, 10 % and 20 % concentrations in 3 replications under *in vitro* conditions by cavity slide method (12). Germination of uredospore was calculated by the formula given below and per cent inhibition of uredospore germination was calculated (13).

Preparation of test chemicals, botanicals, bioagents and ITKs and uredospore collection

To test the concentrations of chemicals, botanicals, bioagents and ITKs of their respective concentrations were prepared using 50 mL of sterilized distilled water and applied to cavity slides. Fresh uredospores were collected from rust pustules using butter paper

and inoculated onto the slides using a sterilized needle. The slides were incubated in a moist chamber at room temperature and control was maintained with distilled water. After 24 hours of incubation, spore germination was observed under a microscope at 10 X magnification across 5 microscopic fields per cavity. The percentage of uredospore germination was calculated using the following formula (12).

Uredospore germination (%) =

$$\frac{\text{Number of uredospores germinated / microscopic field}}{\text{Total number of uredospores / microscopic field}} \times 100$$

The per cent inhibition of uredospore germination over control was calculated by using the formula (11):

$$I = \frac{C - T}{C} \times 100$$

Where,

I = Per cent inhibition of uredospore germination

C = Uredospore germination percentage in the control

T = Uredospore germination percentage in the treatment

Development and evaluation of integrated spray schedule for sorghum rust

A field experiment was conducted during the rabi seasons of 2021 and rabi 2022 at the Main Agricultural Research Station (MARS), UAS, Dharwad, Karnataka to evaluate integrated spray schedules for the management of sorghum rust. The experiment was laid out in a randomised block design (RBD) with 12 treatments and 3 replications. Each plot measured 2.25 × 4.0 m (gross) and 1.35 × 4.0 m (net), with a spacing of 45 × 15 cm. The sorghum variety M 35-1 (Maldandi) was used as the test genotype. It is a tall, purple-stemmed, post-rainy season landrace widely cultivated under dryland conditions in India. The variety is known for stable grain and stover yields across variable sowing dates, good fodder quality, moderate drought tolerance and its extensive use as a genetic donor

in rabi sorghum improvement programmes (14). The crop was sown on 24 October 2021 during rabi 2021 and 16 November 2022 during rabi 2022. Twelve spray schedules were formulated based on their efficacy observed under *in vitro* conditions, integrating fungicides, bioagents, botanicals and ITKs. Each treatment involved 2 foliar sprays applied at 15-day intervals, starting from the onset of disease symptoms. The details of the treatments are presented in Table 1. All recommended agronomic practices were followed uniformly for raising the crop. Disease severity was recorded one day before each spray and at physiological maturity using a 0–9 disease rating scale with slight modifications, where 0 = no visible symptoms and 9 = more than 75 % leaf area affected (15). Disease scores were converted to per cent disease index (PDI) following standard procedures (14). Grain yield was recorded from ten randomly selected and tagged plants per treatment and converted to quintals per hectare (q ha⁻¹). Test weight was determined by recording the weight of 100 grains from each treatment after harvest.

Per cent disease index (PDI) =

$$\frac{\text{Sum of individual ratings}}{\text{Number of leaves examined} \times \text{Maximum disease rating}} \times 100$$

Statistical analysis

Data from all *in vitro* experiments were analysed using a CRD and percentage values of uredospore inhibition were transformed using arc sine ($\sqrt{x/100}$) prior to analysis. The field experiment was analysed following a RBD, with PDI values arc sine transformed, while grain yield and test weight were analysed on original values. Analysis of variance (ANOVA) was performed separately for each season and on pooled data over two seasons after testing homogeneity of error variances and treatment means were compared using the critical difference (CD) test at 5 % probability ($p \leq 0.05$). Treatment effects were considered significant when the calculated F-value exceeded the corresponding tabulated value. All the statistical analysis was done using MS excel and Opstat online software.

Table 1. Integrated spray schedule for sorghum rust management

Treatments	Spray schedule	
	1 st spray	2 nd spray
T ₁	(tebuconazole 50 % + trifloxystrobin 25 %) 75 % WP at 0.05 %	(tebuconazole 50 % + trifloxystrobin 25 %) 75 % WP at 0.05 %
T ₂	hexaconazole 5 % EC at 0.1 %	hexaconazole 5 % EC at 0.1 %
T ₃	Elixer (turmeric extract 25 %, neem extract 50 %) at 1 %	Elixer (turmeric extract 25 %, neem extract 50 %) at 1 %
T ₄	<i>Trichoderma harzianum</i> at 5 g/L + <i>Pseudomonas fluorescens</i> at 5g/L	<i>Trichoderma harzianum</i> at 5 g/L + <i>Pseudomonas fluorescens</i> at 5 g/L
T ₅	Panchagavya at 10 %	Panchagavya at 10 %
T ₆	(tebuconazole 50 % + trifloxystrobin 25 %) 75 % WP at 0.05%	Elixer (turmeric extract 25 %, neem extract 50 %) at 1 %
T ₇	hexaconazole 5 % EC at 0.1 %	Elixer (turmeric extract 25 %, neem extract 50 %) at 1 %
T ₈	tebuconazole 50 % + trifloxystrobin 25 % at 0.05 %	<i>Trichoderma harzianum</i> at 5 g/L + <i>Pseudomonas fluorescens</i> at 5 g/L
T ₉	hexaconazole 5 % EC at 0.1 %	<i>Trichoderma harzianum</i> at 5 g/L + <i>Pseudomonas fluorescens</i> at 5 g/L
T ₁₀	(tebuconazole 50 % + trifloxystrobin 25 %) 75 % WP at 0.05 %	Panchagavya (10 %)
T ₁₁	hexaconazole 5 % EC at 0.1 %	Panchagavya (10 %)
T ₁₂	Unsprayed control	

Results

In vitro evaluation of fungicides against *Puccinia purpurea*

Contact fungicides

The efficacy of 4 contact fungicides was tested at 3 concentrations (0.1 %, 0.2 % and 0.25 %) *in vitro*. The per cent inhibition of the uredospore germination of *P. purpurea* at different concentrations over control was calculated and the results are presented in Table 2. The results revealed that all fungicides significantly ($p \leq 0.01$) inhibited uredospore germination. The highest mean inhibition of germination was observed in chlorothalonil 75 % WP (90.14 %) followed by propineb 70 % WP (88.91 %). Least per cent inhibition of the germination was recorded in zineb 75 % WP (81.53 %). Among different concentrations tested, the highest uredospore germination inhibition of 90.36 % was noticed at 0.25 % concentration and was significantly superior over 0.2 % (87.49 %) and 0.1 % (82.35 %) concentrations. In the case of the interaction effect of fungicides and concentrations, chlorothalonil 75 % WP was recorded significantly highest uredospore germination inhibition of 85.28 %, 91.42 % and 93.71 % and it was on par with propineb 70 % WP recorded 83.75 %, 90.28 % and 92.70 % inhibition followed by mancozeb 75 % WP, which recorded germination inhibition of 82.28 %, 87.04 % and 89.77 % at 0.1 %, 0.2 % and 0.25 % concentrations respectively. Zineb 75 % WP recorded significantly lowest uredospore germination inhibition of 78.10 %, 81.22 % and 85.28 % at 0.1 %, 0.2 % and 0.25 % concentrations respectively.

Systemic fungicides

The efficacy of 6 systemic fungicides were tested at 3 concentrations *in vitro*. The per cent inhibition of the uredospore germination at different concentrations over the control was calculated and the results are presented in Table 3. The results revealed that all fungicides significantly ($p \leq 0.01$) inhibited uredospore germination. Maximum mean inhibition of germination was observed in propiconazole 25 % EC (100 %) and hexaconazole 5 % EC (100%) followed by pyraclostrobin 10 % CS (99.22 %) and tebuconazole 25.9 % EC (98.87 %). Least per cent inhibition of the germination was recorded in validamycin 3 % L (95.69 %). Among different concentrations tested, highest uredospore germination inhibition of 100 % was noticed at 0.1 % concentration and was significantly superior over 0.05 % (99.12 %) and 0.025 % (96.87 %) concentrations. In case of interaction effect of fungicides and

concentrations, at 0.025 % concentration, 100 % inhibition was noticed in propiconazole 25 % EC, hexaconazole 5 % EC followed by pyraclostrobin 10 % CS (97.65 %), tebuconazole 25.9 % EC (96.62 %), difenoconazole 25 % EC (94.62 %) and validamycin 3 % L (92.31 %). At the 0.05 % concentration, cent per cent inhibition was recorded in propiconazole 25 % EC, hexaconazole 5 % EC, tebuconazole 25.9 % EC, pyraclostrobin 10 % CS and difenoconazole 25 % EC followed by validamycin with 94.75 % inhibition. All the six fungicides tested recorded 100 % inhibition of uredospore germination at 0.10 % concentrations.

Combi-product fungicides

The efficacy of 6 combi-product fungicides were tested at 3 concentrations *in vitro*. The per cent inhibition of the uredospore germination at different concentrations over control was calculated and results are presented in Table 4. Results revealed that all fungicides significantly inhibited uredospore germination ($p \leq 0.01$). The highest mean inhibition of germination was observed in tebuconazole 50 % + trifloxystrobin 25 % WG (100 %) and azoxystrobin 25 % + difenoconazole 12.5 % SC (100%) which was on par with hexaconazole 5 % + captan 70 % WP (99.88 %), metiram 55 % + pyraclostrobin 5 % WG (99.64 %) and tricyclazole 18 % + mancozeb 62 % WP (99.55 %). Least per cent inhibition of the germination was recorded in carbendazim 12 % + mancozeb 63 % WP (98.92 %). Among different concentrations tested, maximum uredospore germination inhibition of 100 % was noticed both at 0.1 % and 0.2 % concentrations and was significantly superior over 0.05 % (98.99 %) concentration. In case of the interaction effect of fungicides and concentrations, at 0.05 % concentration, 100 % inhibition was noticed in tebuconazole 50 % + trifloxystrobin 25 % WG (100 %) and azoxystrobin 25 % + difenoconazole 12.5 % SC (100%) which was on par with hexaconazole 5 % + captan 70 % WP (99.65 %) and metiram 55 % + pyraclostrobin 5 % WG (98.92 %) followed by tricyclazole 18 % + mancozeb 62 % WP (98.65 %) and carbendazim 12 % + mancozeb 63 % WP (96.75 %). However, all the tested combi-product fungicides recorded 100 % inhibition of uredospore germination at 0.10 % and 0.20 % concentrations.

In vitro evaluation of commercially available botanicals

The efficacy of six commercially available botanicals was tested at 3 concentrations *in vitro*. The per cent inhibition of the uredospore

Table 2. *In vitro* bioassay of contact fungicides against *Puccinia purpurea*

Sl. No.	Contact fungicides	Per cent inhibition of uredospore germination			
		Concentration (%)			Mean
		0.1	0.2	0.25	
1	chlorothalonil 75 % WP Kavach) ***	85.28 (67.43)*	91.42 (72.97)	93.71 (75.47)	90.14 (71.70)
2	mancozebmancozeb 75 % WP (Indofil M-45)	82.28 (65.10)	87.04 (68.90)	89.77 (71.35)	86.36 (68.49)
3	propineb 70 % WP (Antracol)	83.75 (66.22)	90.28 (71.83)	92.70 (74.32)	88.91 (70.55)
4	Zineb 75 % WP (Zineb)	78.10 (62.09)	81.22 (64.32)	85.28 (67.44)	81.53 (64.55)
	Mean	82.35 (65.16)	87.49 (69.29)	90.36 (71.92)	
	Fungicide (F)	S.Em.±			CD at 1%
		0.41			1.17
	Concentration (C)	0.35			1.02
	F×C	0.71			2.03

** Trade names * arc sine values

Table 3. *In vitro* bioassay of systemic fungicides against *Puccinia purpurea*

Sl. No.	Systemic fungicides	Per cent inhibition of uredospore germination			
		Concentration (%)			Mean
		0.025	0.05	0.1	
1	propiconazole 25 % EC (Tilt)**	100.00 (90.00)*	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)
2	hexaconazole 5 % EC (Contaf)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)
3	tebuconazole 25.9 % EC (Folicur)	96.62 (79.41)	100.00 (90.00)	100.00 (90.00)	98.87 (83.91)
4	Difenconazole 25 % EC (Score)	94.62 (76.59)	100.00 (90.00)	100.00 (90.00)	98.21 (82.30)
5	pyraclostrobin 10 % CS (Header)	97.65 (81.18)	100.00 (90.00)	100.00 (90.00)	99.22 (84.92)
6	validamycin 3 % L (Sheathmar)	92.31 (73.90)	94.75 (76.75)	100.00 (90.00)	95.69 (78.01)
	Mean	96.87 (79.80)	99.12 (84.63)	100.00 (90.00)	
	Fungicide (F)	S.Em.±			CD at 1%
	Concentration (C)	0.86			3.32
	F×C	0.61			2.35
		1.50			5.75

** Trade names * arc sine values

Table 4. *In vitro* bioassay of combi-product fungicides against *Puccinia purpurea*

Sl. No.	Combi-product fungicides	Per cent inhibition of uredospore germination			
		Concentration (%)			Mean
		0.05	0.1	0.2	
1	tebuconazole 50 % + trifloxystrobin 25 % (Nativo 75 % WG) **	100.00 (90.00) *	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)
2	metiram 55 % + pyraclostrobin 5 % (Cabrio Top 60 %WG)	98.92 (84.03)	100.00 (90.00)	100.00 (90.00)	99.64 (86.56)
3	hexaconazole 5 % + captan 70 % (Taqat 75 % WP)	99.65 (86.61)	100.00 (90.00)	100.00 (90.00)	99.88 (88.04)
4	tricyclazole 18 % + mancozeb 62 % (Merger 80 % WP)	98.65 (83.33)	100.00 (90.00)	100.00 (90.00)	99.55 (86.15)
5	carbendazim 12 % + mancozeb 63 % (Saaf 75 % WP)	96.75 (79.61)	100.00 (90.00)	100.00 (90.00)	98.92 (84.025)
6	azoxystrobin 25 % + Difenconazole 12.5 % (Amistar Top 37.5 % SC)	100 (90.00)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)
	Mean	98.99 (84.25)	100.00 (90.00)	100.00 (90.00)	
	Fungicide (F)	S.Em.±			CD at 1%
	Concentration (C)	0.77			2.98
	F×C	0.55			2.10
		1.34			5.16

** Trade names * arc sine values

germination at different concentrations over control was calculated and results are presented in Table 5. The results revealed that all botanicals significantly ($p \leq 0.01$) inhibited uredospore germination. Maximum mean inhibition of germination was observed in Elixer (78.53 %) which was on par with neemzal (77.82 %) followed by Shefaneem (75.97 %). Least per cent inhibition of the germination was recorded in Vijayneem (71.23 %). Among different concentrations tested, maximum uredospore germination inhibition of 79.00 % was noticed at 1.0 % concentration and was significantly superior over 0.5 % (76.17 %) and 0.25 % (71.17 %) concentrations. In the case of the interaction effect of botanicals and concentrations, Elixer was recorded significantly highest uredospore germination inhibition of 74.67 %, 79.59 % and 81.34 % which was on par with Neemazal which is 73.94 %, 79.17 % and 80.36 % and Shefaneem (71.14 %, 77.67 % and 79.10 %) followed by Kaneem which recorded germination inhibition of 70.47 %, 75.42 % and 78.39 % at 0.25 %, 0.5 % and 1.0 % concentrations respectively.

Vijayneem recorded significantly the lowest uredospore germination inhibition of 66.88 %, 70.48 %, 76.34 % at 0.25, 0.5 and 1.0 % concentrations respectively.

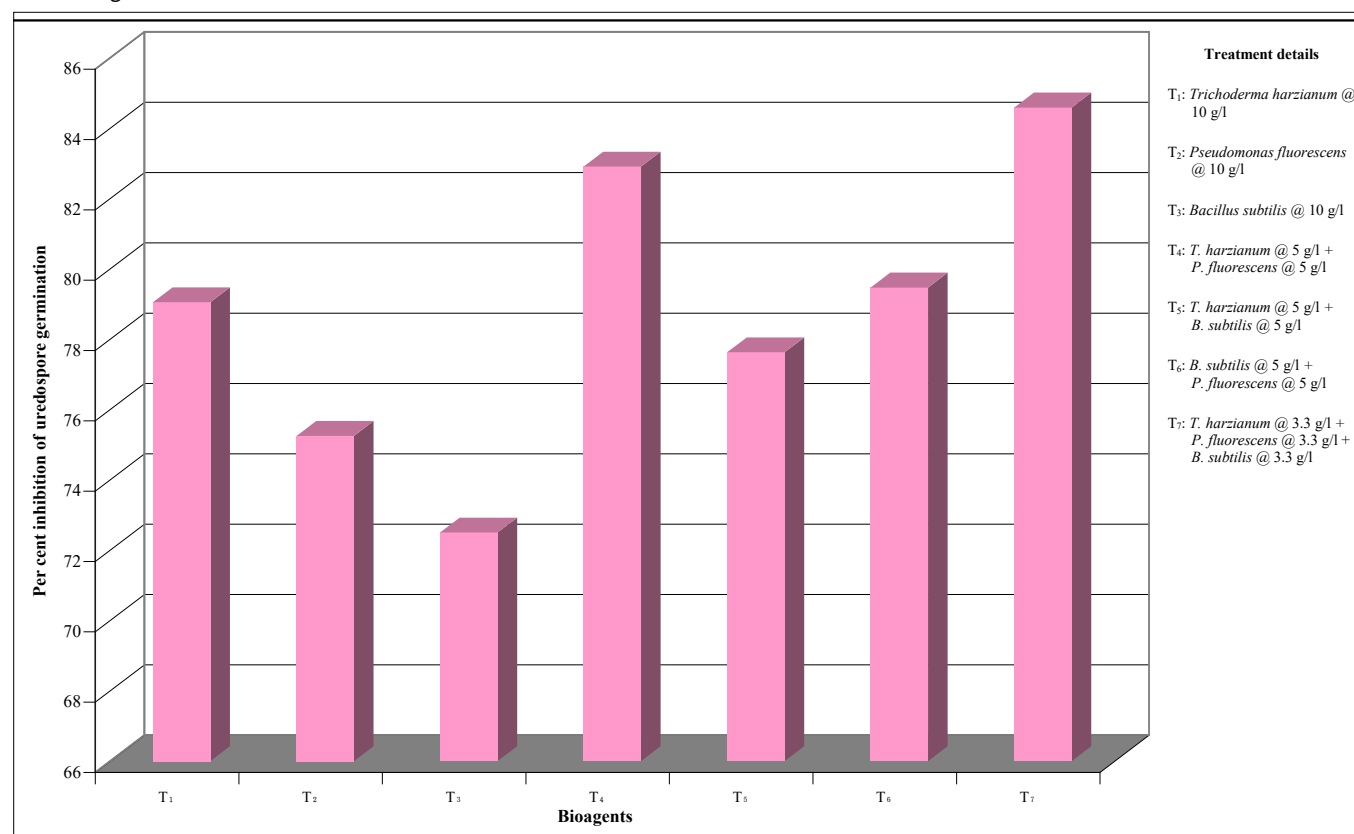
In vitro evaluation of bioagents

The efficacy of bioagents was tested at 3 concentrations *in vitro*. The per cent inhibition of the uredospore germination at different concentrations over control was calculated and results are presented in Fig. 1. A significant inhibitory potential of antagonists was observed at $p \leq 0.01$ against *P. purpurea*. The antagonistic activity of fungal and bacterial bioagents was higher in consortium than that of individual activity. A consortium of 3 bioagents *T. harzianum* (3.3 g/L) + *P. fluorescens* (3.3 g/L) + *B. subtilis* (3.3 g/L) were found effective in inhibition of uredospore germination (84.59 %) and was on par with the consortium of *T. harzianum* (5 g/L) + *P. fluorescens* (5 g/L) (82.91 %) followed by *P. fluorescens* (5 g/L) + *B. subtilis* (5 g/L).

Table 5. Plant-based *in vitro* bioassay for *Puccinia purpurea*

Sl. No.	Botanicals	Per cent inhibition of uredospore germination			
		Concentration (%)			Mean
		0.25	0.5	1.0	
1	Nimbecidine (azadirachtin 0.03 %) **	69.90 (56.73) *	74.67 (59.78)	78.50 (62.37)	74.36 (59.58)
2	Vijayneem (azadirachtin 0.03 %)	66.88 (54.86)	70.48 (57.09)	76.34 (60.89)	71.23 (57.56)
3	Kaneem (azadirachtin 0.03 %)	70.47 (57.08)	75.42 (60.28)	78.39 (62.29)	74.76 (59.84)
4	Neemazal (azadirachtin 1 %)	73.94 (59.30)	79.17 (63.14)	80.36 (63.69)	77.82 (61.90)
5	Elixer (turmeric extract 25 %, neem extract 50 %)	74.67 (59.78)	79.59 (62.84)	81.34 (64.41)	78.53 (62.40)
6	Shefaneem (azadirachtin 0.15 %)	71.14 (57.50)	77.67 (61.80)	79.10 (62.79)	75.97 (60.65)
	Mean	71.17 (57.52)	76.17 (60.78)	79.00 (62.72)	
	Fungicide (F)	S.Em.±			CD at 1%
	Concentration (C)	0.43			1.66
	F×C	0.30			1.17
		0.74			2.87

**active ingredient * arc sine

**Fig. 1.** *In vitro* bioassay of bioagents against *Puccinia purpurea*.***In vitro* evaluation of ITKs against *Puccinia purpurea***

The efficacy of 5 ITKs was tested at 3 concentrations *in vitro*. The per cent inhibition of the uredospore germination of the *P. purpurea* at different concentrations over the control was calculated and results are presented in Fig. 2. The results revealed that all ITKs significantly ($p \leq 0.01$) inhibited uredospore germination. The highest mean inhibition of germination was observed in panchagavya (52.07 %) followed by jeevamruta (45.37 %) and vermiwash (44.50 %) which was at par with each other. Least per cent inhibition of the germination was recorded in cow urine (36.96 %). Among the different concentrations tested, maximum uredospore germination

inhibition of 47.68 % was noticed at 20 % concentration and was significantly superior over 10 % (44.28 %) and 5 % (39.50 %) concentrations. In case of the interaction effect of ITKs and concentrations, panchagavya was recorded significantly highest uredospore germination inhibition of 44.88 %, 54.67 % and 56.67 % followed by jeevamruta (40.88 %, 44.88 % and 50.34 %) and vermiwash (39.17 %, 45.15 % and 49.17 %) at 0.25 %, 0.5 % and 1.0 % concentrations respectively which were on par with each other. Cow urine recorded the significantly lowest uredospore germination inhibition of 34.88 %, 36.54 % and 39.45 % at 5 %, 10 % and 20 % concentrations respectively.

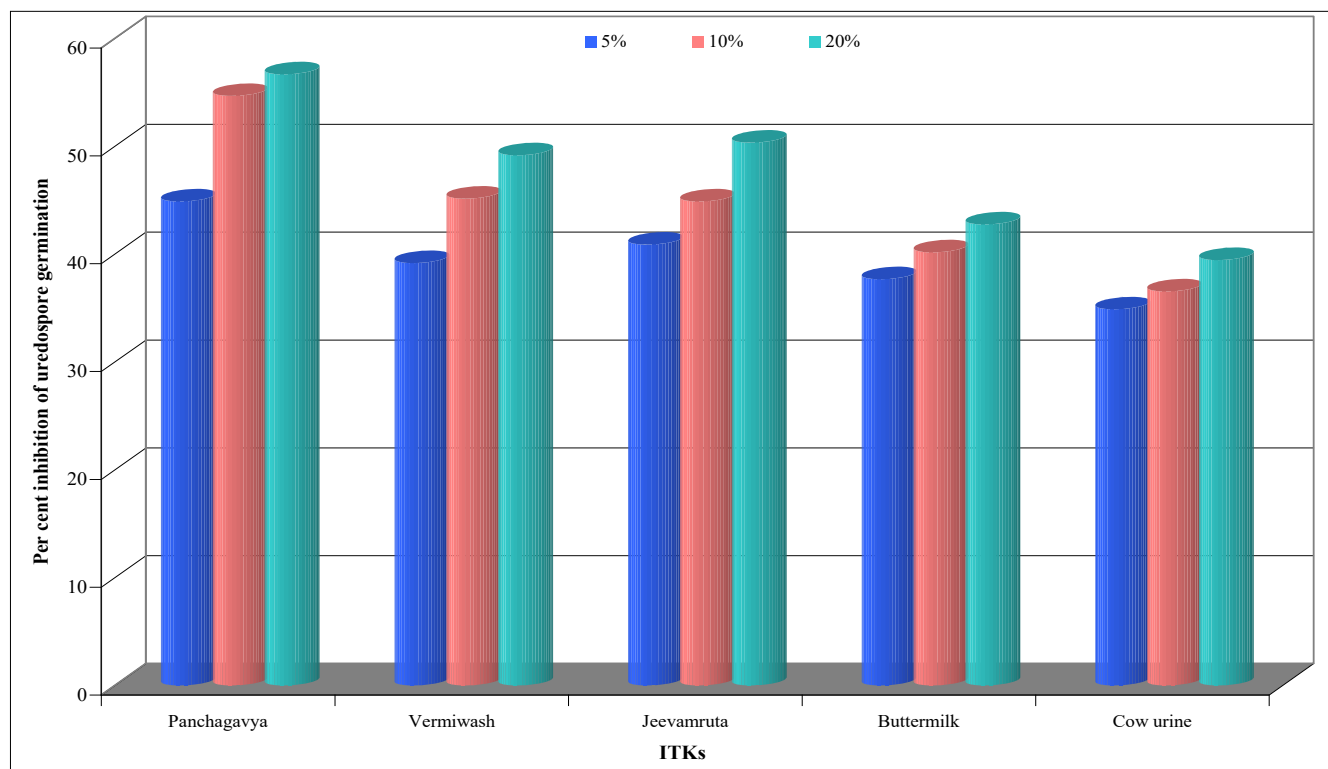


Fig. 2. *In vitro* bioassay of indigenous technical knowledge against *Puccinia purpurea*.

Evaluation of an integrated spray schedule for management of sorghum rust

A field experiment was conducted in RBD with 3 replications during the rabi seasons of 2021 and 2022 at the MARS, UAS, Dharwad on evaluation of developed spray schedule for the management of sorghum rust using susceptible genotype M 35-1. Based on the *in vitro* evaluation results, an effective and economically feasible systemic fungicide (hexaconazole 5% EC), a combi-product fungicide (tebuconazole 50 % + trifloxystrobin 25 % WG), a commercially available botanical (Elixer), a bioagent (*T. harzianum* + *P. fluorescens*) and an ITK (panchagavya) were included in the spray schedule as mentioned in the material and methods section and results are presented in Table 6.

Rust severity

Among the 12 spray schedules evaluated during rabi 2021 and 2022, results revealed that all the spray schedules significantly reduced the rust severity as compared to control. The spray schedule T1 recorded the least per cent disease index of 17.34 and 14.68 at physiological maturity stage which was on par with T2 with per cent disease index of 19.83 and 17.85 during rabi 2021 and 2022 respectively. The next best schedule T8 which recorded per cent disease index of 54.78 and 52.83 which was on par with T6 (55.74 % in rabi 2021 and 52.48 % in rabi 2022), T9 (58.45 % in rabi 2021 and 53.85 % in rabi 2022) and T7 (58.66 % in rabi 2021 and 54.55 % in rabi 2022) and highest per cent disease index of 95.00 % and 90.00 % was recorded in unsprayed control during rabi 2021 and rabi 2022 respectively (Fig. 3).

In the pooled data, spray schedule treatment T1 recorded least per cent disease index of 16.01 % which was on par with T2 (18.84 %) and highest per cent disease index of 92.50 % was recorded in unsprayed control. The spray schedule T1 showed the highest per cent reduction in the severity of 82.69 % over unsprayed control followed by T2 (79.63 %) and T5 (12.23 %) showed the least reduction in rust severity compared to other treatments.

Effect of spray schedule on grain yield, 100-grain weight and dry fodder yield

The results of grain yield, 100 grain weight and dry fodder yield were significant during both the rabi seasons and in pooled analysis (Table 5).

Grain yield (q ha^{-1})

A significantly ($p < 0.05$) highest grain yield of 15.34 q ha^{-1} and 17.17 q ha^{-1} was recorded during rabi 2021 and 2022 respectively; in the spray schedule T1 over other spray schedule. The next best spray schedule during both rabi 2021 and 2022 was T2 which has recorded the grain yield of 14.76 q ha^{-1} and 16.77 q ha^{-1} respectively. Grain yield performance of T8 (12.57 q ha^{-1} and 13.67 q ha^{-1} , during 2021 and 2022 respectively) which was on par with T6 (12.44 q ha^{-1} and 13.58 q ha^{-1} , during 2021 and 2022 respectively) and T9 (12.34 q ha^{-1} and 13.18 q ha^{-1} , during 2021 and 2022 respectively) were found superior over unsprayed control which was recorded 9.16 q ha^{-1} and 10.10 q ha^{-1} , during 2021 and 2022 respectively.

In pooled data also spray schedule T1 was significantly superior (16.25 q ha^{-1}) and was followed by T2 which has recorded the grain yield of 15.76 q ha^{-1} and lowest grain yield of 9.63 q ha^{-1} was recorded in unsprayed control. The spray schedule T1 showed the highest per cent increase in grain yield of 68.80 per cent over unsprayed control followed by T2 (63.71 %) and T8 (36.24 %), while T5 (1.09 %) showed least increase in grain yield compared to other treatments.

Hundred grain weight (HGW)

In the case of HGW, the effect of treatment was similar to earlier parameters. The treatment T1 was found significantly superior over the rest of the treatments with the highest hundred grain weight 4.23 g and 4.54 g in both the years (rabi 2021 and 2022) respectively. This was followed by spray schedule T2 which has recorded 4.12 g and 4.22 g respectively and T6 recorded 4.02 g and 4.12 g respectively during rabi 2021 and 2022 respectively. Least HGW of 3.46 g and 3.53

Table 6. Development and evaluation of integrated spray schedule for the management of sorghum rust during rabi 2021 and rabi 2022

Treatments	Percent disease index			Per cent reduction in disease over control	Grain yield (q/ha)			Per cent increase in grain yield over control	Hundred grain weight (g)				Dry fodder yield (t/ha)		Per cent increase in fodder yield over control	BC ratio
	Rabi 2021		Pooled		Rabi 2022		Pooled		Rabi 2021	Rabi 2022	Pooled	Rabi 2021	Rabi 2022			
T1: tebuconazole 50 % + trifloxystrobin 25 % at 0.05 %-tebuconazole 50% + trifloxystrobin 25 % at 0.05 %	17.34 (24.61)*	14.68 (22.53)	16.01 (23.58)	82.69	15.34	17.17	16.25	68.80	4.23	4.54	4.38	10.29	11.71	11.00	63.93	1.87
T2: hexaconazole 5 % EC at 0.1- hexaconazole 5 % EC at 0.1	19.83 (26.44)	17.85 (24.99)	18.84 (25.72)	79.63	14.76	16.77	15.76	63.71	4.12	4.22	4.17	9.78	10.87	10.32	53.80	1.80
T3: Elixer (1 %) - Elixer (1 %)	78.34 (62.26)	69.85 (56.69)	74.10 (59.41)	19.89	10.04	10.56	10.30	6.96	3.58	3.78	3.68	6.59	7.58	7.18	7.00	1.25
T4: <i>Trichoderma harzianum</i> at 5 g/L + <i>Pseudomonas fluorescens</i> at 5 g/L- <i>T. harzianum</i> at 5 g/L + <i>P. fluorescens</i> at 5 g/L	76.58 (61.06)	68.76 (56.02)	72.66 (58.47)	21.45	10.23	10.64	10.43	8.36	3.56	3.6	3.54	6.77	7.70	7.24	7.90	1.29
T5: Panchagavya (10 %)-Panchagavya (10 %)	83.55 (66.07)	78.75 (62.55)	81.15 (64.27)	12.23	9.23	10.24	9.73	1.09	3.49	3.58	3.53	6.43	7.45	6.94	3.43	1.20
T6: tebuconazole 50 % + trifloxystrobin 25 % at 0.05 %-Elixer (1 %)	55.74 (48.30)	52.48 (46.42)	54.10 (47.35)	41.51	12.44	13.58	13.01	35.10	4.02	4.12	4.07	8.29	10.71	9.50	41.58	1.49
T7: hexaconazole 5 % EC at 0.1-Elixer (1 %)	58.66 (49.99)	54.55 (47.61)	56.60 (48.79)	38.81	12.10	13.14	12.62	31.05	3.97	4.00	4.02	7.97	10.57	9.27	38.15	1.47
T8: tebuconazole 50 % + trifloxystrobin 25 % at 0.05 %- <i>T. harzianum</i> at 5 g/L + <i>P. fluorescens</i> at 5 g/L	54.78 (47.74)	52.83 (46.62)	53.80 (47.18)	41.84	12.57	13.67	13.12	36.24	3.90	3.95	3.92	8.56	10.79	9.67	44.11	1.55
T9: hexaconazole 5% EC at 0.1 - <i>T. harzianum</i> at 5 g/L + <i>P. fluorescens</i> at 5 g/L	58.45 (49.86)	53.85 (47.21)	56.15 (48.53)	39.30	12.34	13.18	12.76	32.50	3.78	3.92	3.85	8.13	10.57	9.35	39.34	1.53
T10: tebuconazole 50 % + trifloxystrobin 25 % at 0.05 % - Panchagavya (10 %)	60.56 (51.10)	58.78 (50.06)	59.67 (50.57)	35.49	10.93	11.34	11.13	15.63	3.72	3.88	3.80	7.23	9.38	8.30	23.70	1.33
T11: hexaconazole 5 % EC at0.1- Panchagavya (10 %)	63.78 (52.10)	59.77 (50.63)	61.77 (51.81)	33.22	9.76	10.86	10.31	7.06	3.69	3.83	3.76	6.90	8.54	7.72	15.05	1.24
T12- Control	95.00 (77.08)	90.00 (71.56)	92.50 (74.10)		9.16	10.10	9.63		3.46	3.53	3.50	6.13	7.29	6.71		1.17
S.Em.±	2.04	1.43	1.60		0.21	0.25	0.23		0.02	0.03	0.02	0.13	0.15	0.14		
CD at 5 %	4.24	2.97	3.32		0.43	0.52	0.47		0.05	0.06	0.05	0.29	0.33	0.30		

Cost of grain at Rs. 3600/q, Cost of dry fodder at Rs. 2000/t, Cost of fungicides/botanicals/ITK's in Rs./Kg or l: tebuconazole 50 % + trifloxystrobin 25 (700/100g), hexaconazole (7), Elixer (1500), *Trichoderma harzianum* (130), *Pseudomonas fluorescens* (150) and Panchagavya (10). Labour charges for two sprays per hectare: Rs. 80 *arc sine values.



a) General over view of IDM plot



b) T₁ - Tebuconazole + Trifloxystrobin 75% WP @ 0.05% - Tebuconazole + Trifloxystrobin 75% WP @ 0.05%



c) T₂ - Hexaconazole 5% EC @ 0.1% - Hexaconazole 5% EC @ 0.1%



d) T₈ - Tebuconazole + Trifloxystrobin 75% WP @ 0.05% - *T. harzianum* 5 g/l + *P. fluorescens* 5 g/l



e) T₁₂ - Control

Fig. 3. Efficacy of spray schedule for the management of sorghum rust.

g was recorded in unsprayed control during rabi 2021 and rabi 2022 respectively. Pooled data has also shown similar trend, T1 recorded HGW of 4.38 g followed by T2 (4.17 g) and T6 (4.07 g) and were superior to the unsprayed control (3.50 g).

Dry fodder yield (t ha⁻¹)

In the case of dry fodder yield, the effect of treatment was like earlier parameters. The spray schedule T1 was found significantly superior over the rest of the treatments with the highest fodder yield of 10.29 t ha⁻¹ and 11.71 t ha⁻¹ during rabi 2021 and 2022 respectively. This was followed by spray schedule T2 which recorded 9.78 t ha⁻¹ and 10.87 t ha⁻¹ respectively and T8 recorded 8.56 t ha⁻¹ and 10.79 t ha⁻¹ respectively during rabi 2021 and 2022 respectively. The least fodder yield of 6.13 t ha⁻¹ and 7.29 t ha⁻¹ was recorded in unsprayed control during rabi 2021 and 2022 respectively.

Pooled data has also shown a similar trend where T1 recorded highest fodder yield of 11.00 t ha⁻¹ followed by T2 (10.32 t ha⁻¹) and T8 (9.67 t ha⁻¹) and were superior to the unsprayed control (6.71 t ha⁻¹). The spray schedule T1 showed the highest per cent increase in dry fodder yield of 63.93 % over unsprayed control followed by T2 (53.80 %) and T8 (44.11 %), while T5 (3.43 %) showed least increase in dry fodder yield compared to other treatments.

Cost-benefit ratio

The estimation of the cost-benefit ratio (B:C ratio) is an important aspect of the economic management of plant diseases. The results (Table 5) revealed that the maximum B:C ratio of 1.87 was obtained with the T1 spray schedule (tebuconazole 50 % + trifloxystrobin 25 % WG at 0.05 %). This was followed by the T2 spray schedule (hexaconazole 5 % EC at 0.1 %), which recorded a B:C ratio of 1.80. The lowest B:C ratio of 1.17 was recorded in the unsprayed control.

Discussion

Integrated disease management (IDM) is an integrated approach to disease control that uses a combination of eco-friendly, economically feasible and compatible methods. IDM can reduce the reliance on chemical fungicides, which have negative impacts on human health, the environment and non-target organisms. Botanicals are a type of plant-based pesticide, bioagents and ITKs that can be used as part of an IDM strategy; they are environment friendly, renewable and relatively inexpensive. They can be used to control diseases by directly inhibiting pathogens or by increasing microbial antagonism. The present investigation uses chemicals, bioagents, commercially available botanicals and ITKs to know the individual and their combinations spray effect against sorghum rust.

In vitro, evaluation of fungicides is a preliminary and useful method to assess their efficacy against pathogens in a short period. It is essential before conducting field experiments. Therefore, *in vitro*, screening of different contact, systemic and combi-product fungicides against *P. purpurea* was carried out in the present study. Four contact fungicides tested at three different concentrations *in vitro* against *P. purpurea*. All fungicides significantly inhibited uredospore germination, with the highest mean germination inhibition observed in chlorothalonil 75 % WP (90.14 %) followed by propineb 70 % WP (88.91 %). Least per cent inhibition of the germination was recorded in zineb 75 % WP (81.53 %). The highest uredospore germination inhibition (90.36 %) was observed at the 0.25 % concentration. chlorothalonil 75 % WP was most effective in inhibiting the uredospore germination of *P. purpurea* due to its multi-

site activities like inhibiting spore germination, affecting various enzymes and other metabolic processes in fungi. Among six systemic fungicides evaluated, 100 per cent inhibition was noticed in propiconazole 25 % EC and hexaconazole 5 % EC at all the concentrations (0.025 %, 0.05 % and 0.10 %) tested which was significantly superior over the rest of the fungicides. Whereas validamycin recorded 92.31 %, 94.75 % and 100 % inhibition at 0.025 %, 0.05 % and 0.10 %, respectively, difenoconazole recorded 94.62 % inhibition at 0.025 % and 100 % inhibition at 0.05 % and 0.10 %. All systemic fungicides showed mean per cent inhibition of uredospore germination of more than 90 % and this may be due to inhibition of ergosterol biosynthesis (triazoles), inhibition of mitochondrial respiration (pyraclostrobin) and abnormal branching of the tips of the pathogen followed by cessation of further growth (validamycin) and similarly propiconazole was found best chemical with 86.03 % uredospore germination inhibition against *P. recondita* f. sp. *tritici* Rob. ex Desm (16, 17).

Among the six combi-product fungicides evaluated, tebuconazole 50 % + trifloxystrobin 25 % WG and azoxystrobin 25 % + difenconazole 12.5 % SC recorded 100 % inhibition at all concentrations (0.05 %, 0.10 % and 0.20 %). Conversely, hexaconazole 5 % + captan 70 % WP, metiram 55 % + pyraclostrobin 5 % WG, tricyclazole 18 % + mancozeb 62 % WP, and carbendazim 12 % + mancozeb 63 % WP recorded 100 % uredospore germination at both 0.10 % and 0.20 % concentrations. The lowest inhibition of uredospore germination of 96.75 % was observed in carbendazim 12 % + mancozeb 63 % WP at a concentration of 0.05 %. All combi-product fungicides exhibited a mean percentage inhibition of uredospore germination exceeding 95 %. This high inhibition can be attributed to their broad-spectrum fungicidal properties, encompassing protective, curative, eradicator and anti-sporulant activities (16). Similar findings were reported, who evaluated four non-systemic, five systemic, and seven combi-product fungicides against *P. tritici* at three concentrations (18). chlorothalonil (0.1 %) among non-systemic and hexaconazole (0.1 %) among systemic fungicides showed the highest inhibition of uredospore germination, while the combi-product hexaconazole 4 % + zineb 68 % was most effective at 0.2 %. Sumi-8 to be the most effective fungicide against *P. porri*, followed by Topas, Kocide-2000 and Dithane M-45, significantly reducing uredospore germination compared to the control (19).

Continuous use of chemical fungicides in the management of diseases invites new problems like air, water, soil, residual toxicity, development of resistance against chemicals by the pathogen and harmful effects on non-target organisms. Consequently, fungicides have been alarming development of a harmful environment for human beings. Contrary to the problems associated with the use of synthetic chemicals, botanicals are environment friendly, renewable, in-exhaustible, indigenously available, readily biodegradable, cost effective and hence constitute a suitable plant protection strategy of integrated disease management. In the present study, screening of commercially available plant products was examined under *in vitro* for their antifungal activity against *P. purpurea*. Maximum mean inhibition of uredospore germination was recorded in Elixer (78.53 %) which was on par with neemzal (77.82 %) followed by Shefaneem (75.97 %). Least per cent inhibition of the germination was recorded in Vijayneem (71.23 %). An increase in concentration increased the inhibition of uredospore germination by all the botanicals. Among botanicals, Neem oil showed the highest inhibition of uredospore germination (88.83 %), followed by Solider (87.03 %) and Sainik

(85.48 %), while Neemark (83.34 %) and Discheck (77.36 %) were less effective (19). Similarly, neem, clove, anthi mandhari and black cumin extracts were inhibited *P. triticina* spore germination by over 98 % (19). Neem plant extracts have demonstrated antibacterial, antifungal and insecticidal properties (19, 20). Neem contains triterpenoids like nimbin, nimbidine and azadirachtin, which exhibit antimicrobial activity by inhibiting microbial growth or disrupting pathogen cell walls. azadirachtin shows strong antifeedant and toxic effects on pathogens (21, 22). turmeric extract possesses broad spectrum antifungal activity (23, 24). Secondary metabolites like curdione, isocurcumenol, curcumenol, curzerene and curcumol from turmeric. These compounds demonstrated inhibitory effects on the growth of *Fusarium graminearum* (25).

In addition to chemical control, employing biological methods for plant disease management is an effective, eco-friendly and alternative approach. Antagonistic organisms play a crucial role in countering pathogens through various mechanisms, including competition, lysis, antibiosis, siderophore production and hyperparasitism (26). The competitive ability of antagonists against *P. purpurea* was studied by the cavity slide method. Antagonistic activity of fungal and bacterial bioagents was higher in consortium than that of individual activity. Consortium of three bioagents *T. harzianum*+ *P. fluorescens* + *B. subtilis* was found effective against germination of uredospore (84.59 %) and was on par with the consortium of *T. harzianum*+ *P. fluorescens* (82.91 %). Next best was *P. fluorescens* + *B. subtilis* (79.47 %) and *T. harzianum* alone (79.05 %) which were on par with each other. Least inhibition was recorded in *B. subtilis* (72.50 %). The impact of the application of *Trichoderma harzianum* HL1 and *T. viride* HL5, singly or in combination, on the uredospores germination of *Puccinia graminis* f. sp. *tritici* was assessed *in vitro*. The combined spore suspension of both isolates showed superiority over the others in the inhibition of uredospore germination (27). Similar studies conducted on *Puccinia striiformis* and on *P. graminis* the efficacy of various bioagents against rust pathogens was assessed (28, 29).

Across the extensive journey from primitive agriculture to modern farming, individuals have evolved numerous farming techniques through age-old experiments and trial-and-error processes. These endeavours aimed to address various challenges encountered in farming operations. The knowledge gained through generations of close interaction with the natural and physical micro-environments is now recognised as ITK. In contemporary terms, ITKs play a significant role in the plant disease management strategy of sustainable agriculture. In the present investigation among the five different ITKs evaluated against inhibition of uredospore germination of *P. purpurea*, irrespective of concentration, panchagavya showed the highest inhibition of uredospore germination (52.07 %) followed by jeevamruta (45.37 %) and vermiwash (44.50 %) which was on par with each other. Whereas the least inhibition of uredospore germination was observed in cow urine (36.96 %). Panchagavya proved highly efficient in inhibiting the uredospore germination of *P. purpurea* can be attributed to the prevalence of fermentative microorganisms, particularly yeast and Lactobacillus. These microorganisms generate beneficial metabolites such as organic acids, hydrogen peroxide and antibiotics, which exhibit effectiveness not only in supporting its growth but also in combating pathogenic microorganisms (30). The similar results were found with several workers on the effectiveness of various ITK's in uredospore germination inhibition of various obligate fungal pathogens (18, 31, 32).

Among the 12 spray schedules evaluated across two rabi seasons (2021 and 2022), the T1 consistently recorded the lowest PDI of 17.34 and 14.68 respectively. This treatment was closely followed by two sprays of T2, which showed PDI of 19.83 and 17.85 respectively. Both treatments were significantly more effective than other spray schedules and the unsprayed control, which exhibited the highest PDI of 95.00 and 90.00 during the same periods. Correspondingly, the highest grain yields of 15.34 q ha⁻¹ and 17.17 q ha⁻¹ were also observed with T1 treatment during rabi 2021 and 2022 respectively, outperforming other schedules. T2 was the next best, yielding 14.76 q ha⁻¹ and 16.77 q ha⁻¹, whereas the unsprayed control yielded only 9.16 q ha⁻¹ and 10.10 q ha⁻¹. The hundred-grain weight followed a similar trend, with T1 achieving the highest weights of 4.23 g and 4.54 g across both seasons, followed by T2 and T6, while the unsprayed control recorded the lowest grain weight. Dry fodder yield mirrored these findings, with T1 producing 10.29 t ha⁻¹ and 11.71 t ha⁻¹, followed by T2 and T8. The estimation of B:C ratio is an important aspect of the economic management of plant disease. The results revealed that the maximum B: C ratio of 1.87 was obtained in T1 spray schedule. This was followed by hexaconazole T2 which had B:C ratio of 1.80. The least cost-benefit ratio of 1.17 was recorded in unsprayed control. The combi- product fungicide (tebuconazole 50 % + trifloxystrobin 25 %) 75 % exhibited a notable reduction in disease severity and a simultaneous increase in sorghum yield at both seasons. This may be due to the excellent protective and curative activity of tebuconazole and the protective action of trifloxystrobin, which also demonstrates mesostemic action (good penetration and re-distribution) and provide stress tolerance to crops against biotic and abiotic factors. hexaconazole at 0.1 % provided the lowest disease intensity and highest fodder yield, while difenoconazole produced the highest grain yield (33). trifloxystrobin + tebuconazole as particularly effective in reducing rust severity and boosting both grain and fodder yields (34, 35) and similarly propiconazole, triadimefon and hexaconazole as superior treatments for leaf rust in wheat (32), while hexaconazole found highly effective against pearl millet rust, particularly when integrated with botanical and ITK approaches like neem oil and cow urine, achieving significant reductions in disease severity and increases in yield (20, 36). Among 5 different IDM modules for the treatment of wheat brown rust, the Module T1, which involved soil application of *T. harzianum* through FYM, seed treatment with *Azotobacter*, and 2 sprayings of zinc (one at the CRI stage and the other at the booting stage), showed the lowest disease incidence of 9.20 %, 11.37 % and 10.00 % at 60, 80 and 100 days after sowing, respectively, during 2018–19, compared to the control (37).

Conclusion

The present study demonstrated that an integrated disease management approach is effective in reducing sorghum rust severity and improving crop productivity under semi-arid conditions. Among the evaluated treatments, 2 foliar sprays of tebuconazole 50 % + trifloxystrobin 25 % WG at 0.05% consistently recorded the lowest percent disease index, highest grain yield, superior hundred-grain weight, maximum dry fodder yield and the highest B:C ratio across two rabi seasons, followed by hexaconazole 5 % EC at 0.1 % applied twice. Integrated schedules combining fungicides with botanicals, bioagents and ITKs provided moderate disease suppression and yield advantages, indicating their potential to reduce chemical dependency. The effectiveness of the superior

spray schedules warrants further validation across multiple locations, seasons and agro-climatic zones to assess their stability, adaptability and long-term sustainability. Adoption of these integrated spray schedules can offer farmers reliable rust management, enhanced grain and fodder yields, improved economic returns and environmentally safer disease control practices, thereby supporting sustainable sorghum production.

Authors' contributions

GRVG conducted the experiment, developed the methodology, and wrote the original draft. KBY corrected the research article and helped in conducting the experiment. DG reviewed, edited and helped in conducting the experiment. CRA reviewed the article and performed fine-tuning of the research article. NGH provided the sorghum genotype M 35-1 for the study and TTB helped in conducting the experiment study. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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