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Integrated management of *Phytophthora capsici* Leon in sweet pepper

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ABSTRACT: Phytophthora blight (*Phytophthora capsici* Leonian) is a devastating disease of sweet pepper in India and worldwide. An integrated management schedule was developed for its management comprising of interventions *viz*., seed treatment with *Trichoderma harzianum* Th-2 + *Bacillus subtilis* BS-2 at 10g/kg seed followed by application of neem cake and farmyard manure enriched with bioagents to planting bed, planting on raised bed, (90-100 cm wide and 15-22 cm height) with silver-black reflective mulch film (30-100 micron thick). Irrigation regulation and soil drainage management to prevent water logging during heavy rains, Removal of weed hosts, collection and destruction of infected leaves and fruits with fungicide treatment. Sequential fungicide application schedule starting with protective foliar sprays of chlorothalonil 75% WP (2g/L) and mancozeb 75% WP (2g/L) in rotation at 15 days interval up to standard meteorological week 40 under Bengaluru weather conditions or until first appearance of leaf lesion at fruit development stage, need based curative sprays and drenching with tank mix of dimethomorph 50% WP(1g/L) + chlorothalonil 75% WP (2g/L) next rotational spray with tank mix of fungicide, dimethomorph 50% WP (1g/L) + mancozeb 75% WP (2g/L). The developed integrated management schedule can be used as an effective strategy to manage Phytophthora blight of sweet pepper in India.

Keywords: Sweet pepper, *Phytophthora* blight, integrated management, IDM, bioagents

INTRODUCTION

Sweet pepper (*Capsicum annuum* L.) is widely cultivated vegetable crop worldwide. It is known by other common names, bell pepper, green pepper, capsicum and by vernacular names, Shimla mirchi in Hindi and Donne menasinakayi in Kannada. It is one of the popular vegetable extensively cultivated throughout India. As per the final estimates of 2018-19, sweet pepper production in India was 497 (000) MT with area of 34 (000) Ha. In India; Karnataka, Himachal Pradesh, Haryana, Jharkhand, Madhya Pradesh, Maharashtra, Tamil Nadu, Uttarakhand, Jammu and Kashmir and Orissa are the major sweet pepper producing states (NHB, 2021). Phytophthora blight incited by *Phytophthora capsici* Leon is the most devastating field diseases of sweet peppers worldwide. Globally the disease and pathogen are widely distributed and has been reported in all the major pepper production areas (CABI, 2019). In India, the disease is of economic interest on sweet pepper in Himachal Pradesh and in hills and plains of Karnataka and Tamil Nadu in South India (Sharma and Bhardwaj, 1976; Chaudhary and Banyal, 2013; Chowdappa *et al*., 2014).

In India, current management of Phytophthora blight in sweet pepper is solely based on fungicide application. Metalaxyl + mancozeb, fenamidone + mancozeb, mancozeb, ziram, copper oxychloride and bordeaux mixture were used in management of fruit rot and leaf blight of bell pepper incited by *Phytophthora nicotianae* var. *nicotianae* (B. de Haan) Waterhouse and *P. capsici*. (Bhardwaj and Sharma, 1985; Chaudhary and Banyal, 2013; Singh, 2015). Fungicide management in India is based on metalaxyl formulations for which intermediate sensitivity is documented in South Indian *P. capsici* isolates (Chowdappa *et. al*., 2014). As on 30.05.2020, in India, there are no fungicides registered for use in sweet pepper for Phytophthora blight management. There is need to evaluate and identify novel fungicides for utilization in integrated disease management of sweet pepper Phytophthora blight in the country.

Different management interventions practiced worldwide for Phytophthora blight management are use of fungicides, organic amendments, planting on raised beds, soil solarization, biosolarization, crop rotation, cover crops, soil plastic mulching, irrigation management, resistant root stocks and varieties (Kim, *et al*., 1997; Hausbeck and Lamour, 2004; Nunez-Zofio *et al.,* 2011; Ji *et al*., 2012; Gilardi *et al.,* 2013; Sanogo and Ji, 2013; Babadoost *et al*., 2015; Lacasa *et al*., 2015; Barchenger *et al*., 2018). In India, apart from fungicide management, there are few reports on integrated management where utilization of compost enriched with microbial biocontrol agents as components along with fungicides were used in managing this pathogen in sweet pepper (Rather *et al*., 2012; Singh, 2015). There is a need

to develop holistic integrated management schedule with novel fungicides, biocontrol agents and good cultural practices as components.

Review of research done in India on *Phytophthora* blight management points out to gaps in identification of different components for integrated management of Phytophthora blight in sweet pepper. Keeping in view the above knowledge and technology gaps, the present study was undertaken with an objective to evaluate the efficacy of fungicides and biocontrol agents for their incorporation in the integrated management of Phytophthora blight in sweet pepper.

MATERIALS AND METHODS

Laboratory and glass house studies were carried out in fungal pathology laboratory of ICAR-Indian Institute of Horticultural Research (ICAR-IIHR), Bengaluru. Field trial on integrated management of Phytophthora blight in sweet pepper was carried out in Hesaraghatta farm of ICAR-IIHR, Bengaluru (13.1362° N, 77.4980° E) during *kharif* season of 2021 under natural epiphytotics of the disease. The trial was carried in a sick plot with history of continuous sweet pepper cultivation and epidemics recorded in previous five years.

Source and maintenance of culture

A highly virulent, previously characterized isolate of *Phytophthora capsici* Leon (Gen Bank accession number MZ474494) maintained in fungal pathology laboratory was used in this work. The pathogen was isolated from infected fruit of sweet pepper sourced from Kadur region of Karnataka. Working culture of the isolate was maintained by periodical culture on carrot agar medium with incubation at 25±2ºC in dark for three to five days (Erwin and Ribeiro, 1996). For long term storage, agar plugs removed from the colony margin were placed in sterile water in 1.5 ml screw capped bottles and stored at room temperature in dark conditions.Virulence and aggressiveness of the isolate was maintained by inoculation and reisolation from sweet pepper fruits at regular intervals.

Planting material

For *in vitro* and *in planta* studies on fungicides and biocontrol agents, plants of open pollinated sweet pepper variety California Wonder were used. California Wonder seeds were obtained from ICAR-Indian Agricultural Research Institute (IARI), Regional Station, Katrain, Himachal Pradesh. In integrated management field studies, in addition to California wonder two popular hybrids *viz.*, Arka Athulya from ICAR-IIHR, Bengaluru, Indra from Syngenta India Private Ltd. and one open pollinated variety 'Arka Mohini' from ICAR-IIHR, Bengaluru were included in the experiment. Crops were raised as per standard package of practice of IIHR for open field and protected cultivation of sweet pepper (Sadashiva *et al*., 2018).

Fungicides and biological control agents (BCAs) evaluation

Antifungal activities of 19 fungicides at different concentrations were evaluated by poison food technique. Stock solutions were prepared by dissolving commercial grade fungicides in water. Autoclaved carrot agar medium was amended with different concentrations of fungicides by adding the stock solution before plating when media was luke warm. Agar plugs of size five mm taken from edge of five days old actively growing culture of *P. capsici* was placed with mycelia side down on carrot agar media plates amended with fungicides at different concentrations. Non amended carrot agar plates served as control. The culture plates were incubated at 28°C for five days in BOD incubator (PHCbi versatile environmental test chamber MLR-352H-PE) in dark. Each fungicide concentration was replicated thrice. Five days after incubation, colony diameters were recorded by measuring two perpendicular colony diameters per plate and averaged. Antifungal activity was determined as per cent inhibition of radial growth, relative to growth on carrot agar plated without fungicide as per the formula given by Vincent (1947).

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

Where, I = per cent inhibition, C = rate of growth in control in mm, T = rate of growth in treatments in mm

In this study 12 biocontrol agents were evaluated in *in vitro* and *in planta* against *P. capsici*. Among 12 biocontrol agents, five were fungi and seven were bacteria comprising three actinobacteria. The biocontrol agents used in this study were previously identified and characterized at ICAR-IIHR, Bengaluru and ICAR-NBAIR, Bengaluru with proven plant growth promoting activity, disease and nematode control efficacy in various horticultural crops (Sriram *et al*., 2010; Chowdappa *et al*., 2013; Rao *et al*., 2017; Prabu *et al*., 2019; Ganeshamurthy *et al*., 2021). *In vitro* bio-efficacy in suppressing mycelia growth of *P. capsici* was carried out by dual culture method (Chowdappa *et al*., 2013). The media used were potato dextrose agar + carrot agar for *Trichoderma* spp., nutrient agar + carrot agar for *Pseudomonas* and *Bacillus* spp. and kenknight media + carrot agar for actinomycetes. Control plate consisted of respective media with 5 mm mycelia plug of *P. capsici*. Mycelial growth was recorded by measuring radial

Table 1. *In vitro* efficacy of contact fungicides against Kadur isolate of *P. capsici*

Fungicide /Concentration in (ppm	Mycelial growth inhibition (%) Mean± SEM				
	500	1000	1500	2000	2500
Mancozeb	80.63±1.05 (63.88±0.75)	87.35± 0.40 (69.14±0.34)	100.00± 0.00 (89.96±0.00)	100.00± 0.00 (89.96±0.00)	100.00± 0.00 (89.96±0.00)
Chlorothalonil	86.17±0.79 (68.15±0.65)	89.72± 0.79 (71.30±0.73)	100.00±0.00 (89.96±0.00)	100.00± 0.00 (89.96±0.00)	100.00± 0.00 (89.96±0.00)
Metiram	62.85± 2.09 (52.44±1.24)	73.12± 1.58 (58.77±1.03)	80.24±1.43 (63.61±1.02)	100.00± 0.00 (89.96±0.00)	100.00±0.00 (89.96±0.00)
Zineb	73.12± 1.05 (58.76±0.68)	81.82± 0.79 (64.74±0.59)	91.30± 1.05 (72.88±1.05)	100.00± 0.00 (89.96±0.00)	100.00± 0.00 (89.96±0.00)
Copper hydroxide	68.77±1.05 (56.01±0.64)	76.68±1.05 (61.11±0.71)	80.63± 1.05 (63.88±0.75)	88.54± 0.40 (70.19±0.36)	100.00±0.00 (89.96±0.00)
Captan	69.96± 0.79 (56.75±0.50)	79.84± 0.68 (63.30±0.49)	90.91± 1.05 (72.48±1.06)	100.00±0.00 (89.96±0.00)	100.00±0.00 (89.96±0.00)
Copper hydroxy chloride	79.45± 0.40 (63.02±0.28)	82.61± 1.05 (65.35±0.80)	100.00±0.00 (89.96±0.00)	100.00± 0.00 (89.96±0.00)	100.00±0.00 (89.96±0.00)
Bordeaux mixture	67.19± 0.79 (55.04±0.48)	78.26± 0.40 (62.19±0.27)	81.42±0.40 (64.44±0.29)	85.38± 0.40 (67.49±0.32)	92.09±0.40 (73.65±0.42)
Propineb	71.94±0.40 (57.99±0.25)	78.26±0.40 (62.19±0.27)	86.17±0.79 (68.15±0.65)	100.00±0.00 (89.96±0.00)	100.00±0.00 (89.96±0.00)
CD1%	Factor A	Factor B	A x B		
	0.87	0.65	1.96		
CV(%)	1.22				

*values in the parentheses are arcsine transformed

Table 2. *In vitro* efficacy of systemic fungicides against Kadur isolate of *P. capsici*

Fungicide/ Concentration (ppm)	Mycelial growth inhibition (%) Mean± SEM					
	100	250	500	1000	1500	2000
Azozystrobin	47.24±0.79 (43.40±0.45)	66.14± 2.08 (54.41±1.26)	74.41± 1.72 (59.61±1.13)	80.31± 0.79 (63.64±0.56)	92.13±0.79 (73.71±0.82)	100.00±0.00 (89.96±0.00)
Mandipropamid	71.65±1.36 (57.81±0.87)	82.68± 0.79 (65.39±0.59)	89.76±0.79 (71.34±0.73)	100.00±0.00 (89.96±0.00)	100.00± 0.00 (89.96±0.00)	100.00±0.00 (89.96±0.00)
Metalaxyl	44.09±0.79 (41.59±0.45)	68.90± 1.04 (56.09±0.64)	80.31± 0.79 (63.64±0.56)	85.43± 1.04 (67.56±0.84)	90.16± 0.39 (71.69±0.38)	100.00±0.00 (89.96±0.00)
Dimethomorph	75.98± 0.79 (60.63±0.70)	85.43±1.04 (67.56±0.84)	100.00± 0.00 (89.96±0.00)	100.00± 0.00 (89.96±0.00)	100.00±0.00 (89.96±0.00)	100.00±0.00 (89.96±0.00)
Fosetyl AL	46.46± 0.79 (42.95±0.45)	68.50±1.04 (55.84±0.64)	78.35± 1.04 (62.26±0.72)	82.68±1.04 (65.40±0.79)	100.00± 0.00 (89.96±0.00)	100.00± 0.00 (89.96±0.00)
CD1%	Factor A	Factor B	A x B			
	1.95	2.13	4.77			
CV (%)	3.10					

values in the parentheses are arcsine transformed

Table 3. *In vitro* efficacy of pre mixed fungicides against Kadur isolate of *P. capsici*

Fungicide/concentration (%)	Mycelial growth inhibition (%) Mean± SEM					
	0.025%	0.05%	0.10%	0.15%	0.20%	0.25%
Cymoxanil 8% + Mancozeb 64% WP	62.60±0.39 (52.28±0.23)	72.05±1.04 (58.07±0.67)	79.13±1.04 (62.81±0.74)	85.04±0.79 (67.23±0.63)	100.00±0.00 (89.96±0.00)	100.00±0.00 (89.96±0.00)
Famoxadone 16.6% + Cymoxanil 22.1% SC	73.23±0.79 (58.82±0.51)	81.50±1.04 (64.51±0.77)	100.00±0.00 (89.96±0.00)	100.00±0.00 (89.96±0.00)	100.00±0.00 (89.9±0.00)	100.00±0.00 (89.96±0.00)
Iprovalicarb 5.5% + Propineb 61.25% w/w WP	52.36±0.79 (46.34±0.45)	67.72±0.79 (55.36±0.48)	76.77±1.04 (61.17±0.71)	80.71±1.04 (63.94±0.75)	85.04±0.79 (67.23±0.63)	90.16±0.39 (71.69±0.38)
Metiram 55% + Pyraclostrobin 5% WG	54.33±0.79 (47.47±0.45)	68.90±1.04 (56.09±0.64)	78.35±1.04 (62.26±0.72)	82.68±1.04 (65.40±0.79)	87.80±0.39 (69.53±0.34)	90.94±1.04 (72.51±1.06)
Metalaxyl M 8% + Mancozeb 64% WP	48.43±1.04 (44.08±0.60)	62.99±0.79 (52.51±0.47)	72.44±0.79 (58.32±0.51)	77.17±1.04 (61.44±0.71)	83.46±0.68 (65.99±0.53)	87.40±0.39 (69.19±0.34)
CD@1%	Factor A	Factor B	A x B			
	0.84	0.92	2.05			
CV (%)	1.42					

values in the parentheses are arcsine transformed

Table 4. *In planta* efficacy of fungicides on collar rot, leaf blight and fruit rot phase of *P. capsici*

Treatment and dosage (per litre)	Collar rot (PDI)	Leaves lesion diameter (mm) Mean±SEM	Fruit lesion diameter (mm) Mean±SEM
Mancozeb 75% WP (2g)	25.93±2.96 (30.52±1.98*)	7.83±0.60 (16.23±0.63)*	22.50±1.04 (28.06±0.80)*
Chlorothalonil 75% WP(2g)	22.96±1.48 (28.60±1.02)	7.17±0.44 (15.51±0.49)	16.83±0.33 (24.21±0.25)
Copper oxychloride 50% WP(3g)	34.81±1.48 (36.14±0.89)	9.17±0.44 (17.61±0.44)	24.17±0.44 (29.43±0.29)
Dimethomorph 50% WP(1g)	5.93±0.74 (14.03±0.93)	2.33±0.17 (8.77±0.32)	9.33±0.33 (17.78±0.33)
Famoxadone 16.6% + Cymoxanil 22.1% SC(1ml)	14.07±1.48 (21.97±1.25)	5.83±0.33 (13.96±0.40)	13.17±0.44 (21.26±0.37)
Cymoxanil 8% + Mancozeb 64% WP (2.5g)	21.48±2.96 (27.49±2.13)	7.33±0.17 (15.71±0.18)	14.17±0.60 (22.09±0.50)
Control	91.11±2.57 (72.99±2.67)	26.17±0.73 (30.75±0.47)	79.83±1.09 (63.31±0.79)
C.D. @1%	5.16	1.34	1.60
SE(m)	1.69	0.44	0.52
C.V. (%)	8.82	4.49	3.07

PDI=Per cent disease index, *values in the parentheses are arcsine transformed

Table 5. *In vitro* and *in planta* bio-efficacy of biocontrol agents against *P. capsici* (Kadur isolate)

Biocontrol agent	Mycelia growth inhibition (%) Mean±SEM	Collar rot severity at 15 dpi(PDI) Mean±SEM	Collar and root rot suppression (%)
Trichoderma harzianum HAR-4B(MTCC 5704)	74.37±1.05 (59.57±0.68)*	31.28±0.82 (33.99±0.51)*	68.06
Trichoderma harzianum Th-2 (NAIMCCSF0033)	75.13±1.31 (60.08±0.87)	30.45±1.65 (33.46±1.03)	68.90
Trichoderma harzianum Th-10 (MTCC 5584)	72.78±0.80 (58.53±0.52)	35.39±0.82 (36.49±0.49)	63.86
Trichoderma asperellum TV-5 (NAIMCC-SF-0032)	62.56±1.60 (52.26±0.95)	44.44±1.43 (41.79±0.82)	54.62
Trichoderma harzianum OTPB3 (NAIMCC-F-03065)	77.05±0.60 (61.36±0.41)	33.74±0.82 (35.50±0.50)	65.55
Streptomyces viridobrunneus Pan Act1	75.61±1.12 (60.39±0.74)	56.79±1.43 (48.89±0.82)	42.01
Streptomyces bullii Pan Act2	58.47±1.22 (49.86±0.71)	62.55±0.82 (52.25±0.49)	36.13
Streptomyces griseorubens Pan Act3	73.37±1.30 (58.92±0.84)	65.02±0.82 (53.72±0.50)	33.61
Bacillus pumilus BP-2 (NAIMCC – B 01213)	76.51±0.92 (60.99±0.62)	41.98±1.43 (40.36±0.83)	57.14
Pseudomonas fluorescens PF-2(NAIMCCSB0038)	18.07±0.93 (25.14±0.70)	43.62±0.82 (41.32±0.48)	55.46
Bacillus amyloliquefaciens BA-2 (NAIMCC-TB2216)	74.40±0.52 (59.58±0.34)	39.51±1.43 (38.92±0.84)	59.66
Bacillus subtilis BS-2 (NAIMCC – B 01211)	74.19±0.41 (59.44±0.27)	32.92±0.82 (35.00±0.50)	66.38
Untreated inoculated control	-	97.94±0.82 (82.02±1.57)	-
CD@1%	1.88	2.29	
SE(m)	0.64	0.78	
CV(%)	2.17	3.07	

PDI= percent disease index, dpi=days post inoculation, *values in the parentheses are arcsine transformed

Table 6. Phytophthora blight severity among four sweet pepper genotypes with three different management interventions in *Kharif* 2021 under open field cultivation

Mean disease severity (PDI)							
Genotype* level of protection				Genotype		Level of protection	
	IP	EP	UP	AA	50.32(45.21)	IP	29.34(32.78)*
AA	28.40(32.19)	49.21(44.53)	73.36(58.90)*	CW	52.85(46.78)	EP	51.26(45.70)
CW	29.34(32.78)	52.43(46.37)	76.80(61.18)	I	51.01(45.67)		
I	29.44(32.85)	48.43(44.08)	75.17(60.09)	AM	54.66(47.91)	UP	76.04(60.69)
AM	30.19(33.32)	54.97(47.83)	78.81(62.57)				
p≤0.05		NS			NS	SeM =0.53, CD=1.54	
CV (%)			13.55				

IP= Improved Practice, EP= Existing Practice, UP= Unprotected, AA= ArkaAthulya, CW= California Wonder, I= Indra, AM= Arka Mohini*Values in the parenthesis are arcsine transformed values of per cent disease index

colony diameters per plate and averaged. Antifungal activity was determined as per cent inhibition of radial growth, relative to growth on carrot agar plated without antagonist as described in previous section.

All the microbial biocontrol agents, three best systemic and contact fungicides identified in *in vitro* evaluation were further evaluated for their bio-efficacy against collar rot, leaf blight and fruit rot phase of *P. capsici in planta*. For bio-efficacy evaluation against Phytophthora root rot, biocontrol agents were applied as seed treatment (10g/kg seed) and as neem cake enriched substrate (1kg in 100kg neem cake). Plants were sown and raised in pots with potting mixture consisting of sterilized soil added with 12% enriched neem cake. All the bioagents were multiplied in broths of selective medium and talc formulated before use. The colony forming unit (CFU) count of fungal antagonists in the formulation was more than 2×10^6 colony forming units per gram and more than 1x 10^8 per gm in case of antagonistic bacteria. The plants were raised under glass house conditions. When seedlings were at three to six leaves stage, they were inoculated with 20 ml of 2×10^4 sporangial suspension using the technique described by Bosland and Lindsey (1991). The experiment was laid out in completely randomized design with each treatment replicated three times with 10 plants. Each replication comprised of 5 pots with three sweet pepper seedlings transplanted.

For fungicide assay, seedlings raised in portrays with sterilized cocopeat were pretreated with fungicides by drenching from collar region in to substrate, followed by application of 5ml sporangial suspension as described previously. Each treatment was replicated thrice with ten plants per replication. Phytophthora root rot severity was assessed 15 days after inoculation by adopting 0-10 scale (Bosland and Lindsey, 1991) where 0= no response, vigorous healthy (as in uninoculated control); 1=slight root darkening, vigorous healthy; 3=brown roots, slight stunting very small lesions on stems; 5=brown roots, small lesions on stems, lower leaves wilted, stunted plants; 7=brown roots, large lesions on stems, girdling whole plant wilted and stunted and 9= death. Percent disease index (PDI) was calculated for each treatment. Phytophthora inoculated and biocontrol or fungicide non treated plants served as control. PDI was calculated using the formula

$$\text{PDI} = \frac{\text{Sum of all numerical disease rating}}{\text{Total number of observations} \times \text{Maximum disease grade}}$$

For bio-efficacy evaluation against leaf blight and fruit rot, detached leaves and fruits assay were carried out as per the method described by Chowdappa *et al.* (2014) and Foster and Hausbeck (2010). For this sweet pepper cv. California wonder crop was cultivated in green house. When plants were at principal growth stage development of fruits, they were given foliar spray of test fungicides. Green fruits and leaves were detached from crown of the plants after treatment and were carried in to laboratory for assay. The detached leaves and fruits were placed on 180 mm Petri dish placed in transparent plastic storage boxes. Each treatment comprised three replicates with five leaves and fruits in each replication. Fruits and leaves were inoculated with five mm mycelia plug from margin of 5 days old actively growing culture of *P. capsici*. Fruit and leaves inoculated with sterile carrot agar medium plugs served as control. Inoculated fruits and leaves were incubated for one week under 12 hour cycle of alternate dark and light with 85% relative humidity. Observations on lesion diameter and visible pathogen growth diameter were taken at 5 dpi on fruits and 7 dpi on leaves. To measure diameter, two perpendicular measurements were taken and averaged.

Integrated management

Integrated management experiment was laid out in 4×3 factorial randomized complete block design. First factor was sweet pepper genotypes at four levels and second factor was management modules at three levels. There were three blocks in the experiment. In first factor, there were four genotypes. It included two popular hybrids; Arka Athulya from ICAR-IIHR, Bengaluru and Indra from Syngenta India Pvt. Ltd. and two open-pollinated varieties; California Wonder from IARI, Regional Station, Kullu Valley, Katrain, Himachal Pradesh and Arka Mohini from ICAR-IIHR, Bengaluru. All the genotypes belonged to green segment and are recommended for open field cultivation in *Kharif* and *Rabi* seasons in Karnataka.

The second factor was management interventions with three levels. There were three treatments; first treatment was improved integrated management practices developed out of current research T1= seed treatment & nursery cocopeat enrichment with *Trichoderma harzianum* Th-2 + *Bacillus subtilis* BS-2. Application of farm yard manure and neem cake (18% oil content) bioenriched with *Trichoderma harzianum* Th-2 + *Bacillus subtilis* BS-2 to planting bed at 600 kg per acre. Planting on raised bed (90-100 cm wide and 15-22 cm height) with silver-black reflective mulch film (30-100 micron thick). Proper soil drainage to prevent water logging during heavy rains. Removal of infected low lying diseased or soil touching leaves. Sequential fungicide application schedule; initial protective foliar sprays with chlorothalonil 75% WP and mancozeb 75% WP in rotation at 2g per litre at 15 days interval

up to standard meteorological week 40 under Bengaluru weather conditions or until first appearance of leaf lesion at crop growth stage fruit development. On notice of first foliar blight lesions, need based curative sprays and drenching with tank mix of dimethomorph 50% WP (1g/L)+ chlorothalonil 75% WP (2g/L), next rotational spray with tank mix of fungicide, dimethomorph 50% WP (1g/L) + mancozeb 75% WP (2g/L). Second treatment was existing management practice (T2) = Application of farmyard manure without bioenrichment. Shallow bed planting, with black polyethylene (30-100 micron) mulching. Protective foliar spray of copper oxychloride 50% WP (2.5 g/L) and mancozeb 75% WP (2.5 g/L) at fortnightly intervals followed by curative spray and drenching with metalaxyl 8% + mancozeb 64% WP (2.5g/L) at ten days intervals. Third treatment was untreated control with application of farmyard manure without microbial bioenrichment, planting on shallow bed without mulching and no fungicide intervention for Phytophthora blight management.

Seedlings were raised on plastic portrays filled with sterilized cocopeat media. About 42-45 day old seedlings with four to five true leaves were transplanted. The seedlings were subjected to hardening prior transplanting. Seedlings were transplanted on bed of 100 cm wide with 50 cm between beds and 45 cm spacing between rows and plants. To boost vegetative growth, buds from the first and second nodes were pinched off. Unproductive branches below the first node were also clipped. Staking was provided by using GI wires strung across bamboo stakes of 6 feet height. In all the treatments, sucking pests were managed with foliar application of imidacloprid 17.80% SL (0.5ml/L) 10 days after transplanting (DAT), azadirachtin 01.00% EC (10000 ppm) (3ml/L) and fenazaquin 10 % EC (2 ml/L) @ 20 DAT, spinosad 45.00% SC (0.32 ml/L) @ 30 DAT and neem soap (10 g/L) @40 DAT. To manage fruit borers three foliar sprays of indoxacarb 14.50% SC (1.34 ml/L) and spinetoram 11.70%SC (1ml/L) were given in rotation at fruiting stage at fortnightly intervals. To manage virus diseases, beside insecticide sprays, three foliar sprays of micronutrient formulation Arka Vegetable special (3g/L) and sagarika a sea weed extract (28% w/w) (2ml/L) were applied at 30 DAT, 45 DAT and 60 days after transplanting. Powdery mildew and leaf spot diseases were managed with foliar application of sulphur 80% WP (3g/L) and carbendazim 50% WP (1g/L). Soil drenching with captan 75% WP (2.5g/L) was given at 10 DAT to manage root rot and wire stem.

Fruits were harvested at green stage. Fruit yield data from all the pickings from each plot was pooled and expressed as tonnes per hectare. At each harvest, observations on marketable and non marketable fruits were recorded. Disease severity in field were rated based on a scale of 0–5 adopted from Kim and Hwang (1992), where 0 = no visible disease symptoms, 1= leaves slightly wilted with black lesions beginning to appear on stems or 10–29% of the entire plant diseased, 2 = 30–49% of the entire plant diseased, 3= 50–69% of the entire plant diseased, 4= 70–90% of the entire plant diseased, 5= dead plant. Percent disease index (PDI) was calculated for each treatment based on scored values.

Statistical analysis

Disease severity index data and percent mycelial growth inhibition data were subjected to arcsine transformation before statistical analysis. Yield, mycelial growth inhibition and disease severity data were subjected to ANOVA for statistical significance among different treatments at significance level 1 per cent and 5 per cent.

RESULTS AND DISCUSSION

Fungicide evaluation

The results on *in vitro* and *in planta* evaluation of contact, systemic and pre mix fungicides are presented in the tables 1, 2, 3, and 4. In the current study, dimethomorph was significantly superior over other systemic and contact fungicides in both *in vitro* and *in planta* evaluation. Dimethomorph belongs to carboxylic acid amides group with low to moderate risk of fungicide resistance development. In India, there are no previous reports on its use in sweet pepper Phytophthora blight management. In other parts of the globe, dimethomorph has been extensively used as foliar spray and soil drenches in *P. capsici* management (Matheron and Porchas, 2000; Jackson *et al*. 2012; Meyer and Hausbeck, 2013; Babadoost, *et al*., 2015; Babadoost and de Souza, 2019). The next best systemic fungicide was mandipropamid. Mandipropamid has been previously used as foliar and drenches for Phytophthora blight management in sweet pepper (Meyer and Hausbeck, 2013; Jackson *et al*., 2012; Qi *et al*., 2012.). Among premix fungicides, cymoxanil based pre mix fungicides, famoxadone 16.6% + cymoxanil 22.1% SC and cymoxanil 8% + mancozeb 64% WP were effective both in *in vitro* and *in planta* evaluation. Our results agree with previous work of (Chaudhary and Banyal, 2013) who have reported efficacy of cymoxanil 8% + mancozeb 64% WP @ 0.25 per cent with 57.6 per cent control of leaf blight and 67.5 per cent fruit rot control. Babadoost *et al*. (2015) have reported famoxadone + cymoxanil (Tanos 50WDG) as one of the effective fungicides for control *of P. capsici* in sweet pepper.

Table 7. Marketable yield in integrated management evaluation in *Kharif* 2021 under open field cultivation

Mean marketable yield (t/ha)							
Genotype* level of protection				Genotype		Level of protection	
	IP	EP	UP	AA	18.70	IP	28.06
AA	32.22	17.78	6.11	CW	16.11	EP	16.53
CW	27.78	13.33	7.22	I	20.18		
I	30.56	21.11	8.89	AM	13.70	UP	6.64
AM	21.67	13.89	5.56				
p≤0.05	SeM =1.05, CD=3.08			SeM =0.61, CD=1.78		SeM =0.65, CD=1.68	
CV (%)				10.61			

IP= Improved Practice, EP= Existing Practice, UP= Unprotected, AA= ArkaAthulya, CW= California Wonder, I= Indra, AM= ArkaMohini

PDI=Per cent disease index, *values in the parentheses are arcsine transformed

In previous works on fungicide management of *P. capsici* and *P. nicotianae* in sweet pepper in India (Bhardwaj and Sharma 1985; Chaudhary and Banyal, 2013; Singh 2015) metalaxyl was one of the main fungicides used to control sweet pepper Phytophthora blight. Metalaxyl based compounds were reported as effective fungicides both in *in vitro* assay and field evaluation. Our results contradict above results; the isolate tested was less sensitive to metalaxyl based compounds. Resistance to metalaxyl and mefenoxam in *P. capsici* isolates of sweet pepper isolates is already reported in other parts of the globe (Parra and Ristaino, 2001; Cerkauskas *et al*., 2015).In India, intermediate sensitivity is documented in South Indian *P. capsici* isolates (Chowdappa *et. al.,* 2014). The three best protectant fungicides in current evaluation were chlorothalonil 75% WP followed by mancozeb 75% WP and copper oxychloride 50% WP. All these fungicides are generally considered as a low risk group without any signs of resistance developing to the fungicides. In fungicide evaluation by Singh (2015), prophylactic spray of copper oxychloride 50% WP @0.3% was found effective for field management of *P. capsici* management in sweet pepper. Similarly in *P. nicotianae*-sweet pepper pathosystem, six sprays of copper oxychloride 50% WP @0.3% at 10-day intervals was reported as most effective fungicide in checking the disease (Bhardwaj and Sharma (1985). The identified fungicides can be effectively used as components in integrated management of Phytophthora blight in India.

Biocontrol agents evaluation

The results on dual culture assay and pot evaluation of antagonists against *P. capsici* (Kadur isolate) is presented in Table 5. Among *Trichoderma* bioagents evaluated, *T. harzianum* OTPB3, *T. harzianum* HAR4B and *T. harzianum* IIHR-Th-2 were at par with each other in mycelia growth inhibition in *in vitro* evaluation. Among bacterial antagonists, *Streptomyces viridobrunneus* Pan Act1, *Bacillus pumilus* BP-2, *Bacillus amyloliquefaciens* BA-2 and *Bacillus subtilis* BS-2 were effective while *Pseudomonas fluorescens* (Strain No. IIHR-PF-2) did not show *in vitro* efficacy. All the antagonists were further evaluated in pots for collar rot disease suppression. The level of suppression varied between 33.61 to 68.90%. Among bacterial antagonists, *Bacillus subtilis* BS-2 was statistically superior over others with 66.38% disease suppression, while actinobacteria which were effective *in vitro* did not show bio-efficacy in pot evaluation. Among fungal antagonists, *T. harzianum* Th-2 showed highest disease suppression of 68.90%, but was statistically at par with *T. harzianum* HAR-4B and *T. harzianum* OTPB3. Our results on biocontrol agents conform to results of previous works in India and abroad. *Trichoderma harzianum* has been effectively used as seed and root treatments to manage *P. capsici* in sweet pepper (Ahmed *et al*., 1999; Ahmed *et al*., 2000; Singh *et al*., 2015), in chilli (Sriram *et al*., 2010) and in black pepper (Umadevi and Anandaraj, 2019). In another work from India, *T. harzianum* OTPB3 was identified with *in vitro* antibiosis, growth stimulation and induction of systemic resistance in tomato seedlings against *Phytophthora infestans* the late blight pathogen (Chowdappa *et al*., 2013).

Bacillus subtilis has been reported as an effective bioagent against *P. capsici* in different vegetable crops; in sweet pepper (Lee *et al*., 2008), in red pepper as consortia of *Bacillus subtilis* AH18 and *Bacillus licheniformis* K11 (Lim and Kim, 2010), in tomato (Sharma *et al*., 2015). *Bacillus subtilis* OTPB1 is reported as a plant growth -promoting rhizobacteria that enhanced growth and induce systemic defense responses in tomato plants against *Phytophthora infestans* (Chowdappa *et al*., 2013).

Based on the results of *in vitro* and pot studies, two antagonists were selected, one each from bacterial and fungal functional groups to be included as component in integrated management trial. From bacterial antagonists

group *Bacillus subtilis* BS-2 was chosen as it showed consistent *in vitro* and *in planta* bio-efficacy. From fungal antagonist group, *Trichoderma harzianum*Th-2 was chosen although it was at par with *T. harzianum* HAR-4B and *T. harzianum* OTPB3 as it is a registered bio-pesticide (under the Insecticides Act, 1968) for use in tomato, brinjal, carrot and okra against soil borne pathogens. The bio-efficacy results generated can be used for label expansion for this biopesticide for *P. capsici* management in sweet pepper in India.

Integrated management

Results on Phytophthora blight severity in different management interventions is presented in Table 6. There was statistically significant difference between different levels of protection. Lowest disease severity was recorded in improved management practices between 28.40% to 30.19% compared to 48.43% to 49.21% in existing practices and 73.36% to 75.17% in untreated control. Phytophthora blight severity was significantly low in integrated management practices compared with existing practice. The disease severity was not significant among genotypes and in genotypes × level of protection interaction indicating that all the genotypes were susceptible and showed equal response to different management interventions with respect to Phytophthora blight severity.

Marketable fruit yield per ha of four different genotypes Arka Athulya, Arka Mohini, Indra and California wonder is presented in Table 7. There was significant difference in yield among different genotypes. Highest yield was recorded in Arka Athulya (32.22 t/ha) followed by Indra (30.56t/ha), California wonder (27.78 t/ha) and Arka Mohini (21.67 t/ha). This difference in yield may be attributed to inherent yielding potential of genotypes. Arka Athulya and Indra are high yielding hybrids whereas Arka Mohini and California wonder are open pollinated varieties. Significant difference was noticed with reference to yield among different management interventions. Highest yields were recorded in improved management practices treatments which were statistically superior over existing practices and untreated control. This indicated that the improved management interventions were effective in protecting plants against Phytophthora blight. Genotype×treatment interactions were significant with respect to yield parameter. This may be due to differential response of genotypes to mulching and other components used in integrated management. Sharma *et al.* (2011) have previously reported genotypic differences in growth, yield and quality attributes of capsicum (*Capsicum annuum*) under black polyethylene mulch.

In different sweet pepper production regions of world, more than single component is integrated to manage *P. capsici*. The management strategies followed are combining irrigation management with fungicides (Biles *et al*., 1992), resistant cultivar with fungicides (Foster and Hausbeck, 2010), organic amendments with soil plastic mulching (Nunez-Zofio *et al*., 2011), fungicides with biocontrol agents (Rather *et al*., 2012) and grafting with compost treatment (Gilardi et al., 2013). Hausbeck and Lamour (2004) have suggested integrated management measures that could be followed from pre-plant to post-harvest stage for *P. capsici* management in vegetable crops.

In India there are two previous works on integrated management of Phytophthora blight in sweet pepper. Singh (2015) developed an integrated management practice for effective management of *P. capsici* in sweet pepper in Himachal Pradesh. The management practices were; prophylactic spray either with fenamidone 10% + mancozeb 50% WG @0.2% or metalaxyl 8% + mancozeb 64% WP @0.25% followed by four periodic spray of copper oxychloride @0.3% applied in combination with soil application of neem cake and *Trichoderma harzianum* @2.5kg/50kg FYM/ha besides mulching of treatment. Rather *et al.* (2012) found that seed treatment+ seedling treatment + spraying of carbendazim + metalaxyl proved most effective and recorded 59.8% reduction in wilt complex in bell pepper (*Capsicum annuum* L.) var. California Wonder in Jammu and Kashmir. The wilt complex was reported to be caused by pathogens, *Fusarium oxysporum*, *P*. *capsici*, *Rhizoctonia solani* and *Sclerotium rolfsii*. In the same study, integration of captan + metalaxyl as spray application along with soil application of *Trichoderma harzianum* and *Trichoderma virens* was also proved superior compared to their individual treatments in management of wilt disease in bell pepper. There are several disadvantages in adopting above developed integrated management practices. Metalaxyl based fungicides are included for which already intermediate resistance is reported. The other fungicides fenamidone 10% + mancozeb 50% WG is currently not available in market in India. Both these studies advocate blanket application of fungicides, without taking in to consideration epidemic-associated factors that contribute for disease spread and persistence. In addition other components like cultural practices and host range is not taken in to account. The integrated Phytophthora blight management schedule developed in the present study is a holistic strategy developed with coordinated use of multiple components like cultural, biocontrol agents and need based fungicide application with decision support based on epidemiological aspects of sweet pepper Phytophthora blight in Bengaluru conditions.

The integrated management interventions include seed treatment with *Trichoderma harzianum* Th-2 + *Bacillus subtilis* BS-2 at 10g/kg seed followed by application of neem cake and farmyard manure bioenriched with biocontrol agents to planting bed. Planting on raised bed (90-100 cm wide and 15-22 cm height), with silver-black reflective mulch film (30-100 micron thick). Irrigation regulation along with soil drainage management to prevent water logging during heavy rains. Removal of weed hosts, collection and destruction of infected leaves and fruits with fungicide treatment. Sequential fungicide application schedule comprising of initial protective foliar sprays with chlorothalonil 75% WP (2g/L) and mancozeb 75% WP (2g/L) in rotation at 15 days interval up to standard meteorological week 40 under Bengaluru weather conditions or until first appearance of leaf lesion at crop growth stage fruit development. On notice of first foliar blight lesions, need based curative sprays and drenching with tank mix of dimethomorph 50%WP (1g/L)+ chlorothalonil 75% WP (2g/L), next rotational spray with tank mix of fungicides dimethomorph 50% WP (1g/L) + mancozeb 75% WP (2g/L). At present there are no sweet pepper varieties available in India for commercial production with Phytophthora blight resistance. In the absence of resistant varieties, the integrated management schedule developed could be followed to effectively manage this disease in regions of the country where the disease is prevalent in severe form. The developed management schedule will serve as baseline management schedule for further refinement taking in to consideration fungicide sensitivity among isolates prevailing in a particular geography.

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