CHAPTER

Updates on phytoplasma diseases associated with weeds acting as alternate hosts in Asian countries

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1. Introduction

Weeds are the pioneering species in ecological succession. Liebman et al. (2001) defined weeds as "the plants that are especially successful at colonising disturbed, but potentially productive sites, and maintaining their abundance under conditions of repeated disturbance." In a controlled system such as agriculture and horticulture, the native climax vegetation is replaced with domesticated plant species chosen for their commercial value. Agricultural systems are designed to maintain conditions most suitable to the growth of the particular crop species, thus are imposed with repeated disturbance. This disturbance undoubtedly evokes a "weed response" from nature, struggling to bring out ecological succession. Weeds compete with crops for the resource, causing yield losses. Weeds left undisturbed for a long time get the succession to climax species and becomes home to many parasites struggling to survive in the absence of a host. They act as alternate hosts for many pathogens ranging from viruses, bacteria, fungus to insect pests. The presence of weeds significantly influences disease incidence. The importance of these weeds in phytoplasma epidemiology has been vastly discounted. However, numerous researchers have reported many weeds as reservoirs of these destructive pathogens with different distribution and abundance in the Asian subcontinent.

Phytoplasmas are phloem inhabiting, cell wall-less, obligate plant pathogens that belong to class mollicutes (Bertaccini and Lee, 2018). They are vectored through hemipteran insects and multiply in the plant phloem tissue and insect hemolymph, inducing a wide array of symptoms in plant hosts. Many different phytoplasmas may infer the same types of symptoms in other plants. Various phytoplasma strains are associated with the diseases in thousands of plant species, including fruits, trees, vegetables, ornamentals, oil crops, and weeds (Rao et al., 2017c). The phytoplasma-infected weeds show a wide range of symptoms, including chlorosis of leaves leading to white leaf, leaf yellows,

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little leaf, witches' broom, bunchy top, phyllody, and virescence (Biswas et al., 2014; Mall et al., 2020; Tiwari et al., 2014;). Weed diseases associated with phytoplasmas have been reported predominantly in south-eastern Asian countries and Europe (Marcone et al., 2016). Polyphagous insects feed on the infected weeds and spread phytoplasmas to field crops. Insect vectors of phytoplasmas are known to travel up to a few hundred meters (Bertaccini et al., 2019). Studies were conducted to explore the role of weeds as a reservoir of phytoplasmas in various economically important crops. More than 80 weed species reported as phytoplasma hosts related to different phytoplasma species viz. '*Candidatus* Phytoplasma asteris,' '*Ca.* P. aurantifolia,' '*Ca*. P. australasia,' '*Ca*. P. ziziphi,' '*Ca*. P. trifolii,' '*Ca*. P. cynodontis' throughout Asia (Asudi et al., 2016; Li et al., 2012; Rao et al., 2017c; Thorat et al., 2016; Yadav et al., 2015). This review aims to provide an up-to-date summary of phytoplasma diseases associated with various weed plants in Asian countries.

2. Weeds as a reservoir of phytoplasmas

Weeds affected by phytoplasma-related diseases play an essential role as an alternative host of phytoplasmas. The infected weeds pose a significant threat to commercial crops around them. *Cynodon dactylon* is the first Indian weed reported with phytoplasma infection. Singh et al. (1978) reported the existence of phytoplasma in phloem cells in *C. dactylon*. After that, Muniyappa et al. (1979) observed white leaf symptoms in *C. dactylon* in 2007, while Rao et al. (2007) reported the association of BGWL/16SrXIV group phytoplasma with Bermuda grass white leaf (BGWL) disease. Later on, Kumar et al. (2015) reported witches' broom, leaf chlorosis, stunting and shortened rhizomes/stolons in *C. dactylon* and reported the insect vector *Exitianus indicus* responsible for the transmission of '*Ca.* P. cynodontis' (BGWL/16SrXIV group) in nature. The phyllody and witches' broom symptoms on *Parthenium hysterophorus* were firstly reported by Padmanabhan (1982). Typical Rice Dwarf symptoms were observed in phytoplasma-infected *Echinochloa colonum* plants. These symptoms were also recorded in rice crop plants following phytoplasma transmission from diseased *E. colonum* plants (Reddy and Jeyarajan, 1988). The perennial rhizomatous grass *Imperata arundinacea* showed white leaf disease associated with a phytoplasma infection (Rao and Singh, 1990). Association of 16SrI, 16SrII, 16SrVI, and 16SrXIV group phytoplasmas was reported with yellowing and witches broom symptoms of *Cannabis sativa* and *Achyranthes aspera* (Chaube et al., 2015; Kumar and Rao, 2017; Mall, 2009; Raj et al., 2008b, 2009b). Recently, '*Ca.* P. sacchari' (16SrXI-B) was found associated with *Cannabis* sp. which acted as an alternative host of sugarcane grassy shoot disease (Maurya et al., 2020). The disease symptoms on various weeds are leaf yellowing on *Ageratum conyzoides* and *Amaranthus* spp., little leaf on *Achyranthus*, veinal chlorosis on *Digitaria san guinalis,* bunchy shoot on *Cenchrus ciliaris*, phyllody on *Phyllanthus fraternusas* reported from north India (Arocha et al., 2008; Kumar and Rao, 2017; Mall et al., 2007; Nabi et al., 2015; Yadav et al., 2014). The little leaf disease of *Ranunculus scleratus* was reported associated with '*Ca.* P. cynodontis' (16SrXIV, BGWL group) (Kumar et al., 2015). Various diseases in *Phalaris* sp. and *Oplismenus burmannii* were found to be associated with peanut witches' broom (16SrII) phytoplasmas (Yadav et al., 2015; Mall et al., 2015). Recently, *Setaria verticillate* was confirmed hosting a phytoplasma strain of '*Ca.* P. australasia' (16SrII-D) (Mall et al., 2020).

3. Phytoplasma diagnosis and genetic diversity

During the early decades of research, the detection of phytoplasma infection was purely based on disease symptoms and microscopy involving DAPI (DNA specific 6-diaminido-2-phenylindole) and TEM (transmission electron microscope) (Deeley et al., 1979; Purohit et al., 1978). Later the serological methods and DNA probe-based methods came forth (Viswanathan, 2001). With advances in molecular biology, the techniques used for detection, identification, and characterization of phytoplasmas became more sophisticated. The methods include PCR, nested PCR, q-PCR, PCR-RFLP-induced assays, LAMP (loop-mediated isothermal amplification), and digital droplet PCR (Bahar et al., 2018; Hodgetts et al., 2011; Marcone, 2014). These methods gained popularity due to their accuracy and sensitivity. Newer approaches like NGS (next-generation sequencing) are not a method of choice for detection, but it serves as a credible method for identification and molecular characterization. Detection methodologies and equipment having cost-effectiveness and being used for on-field application need to be developed.

Phytoplasmas associated with weed show a wide geographical distribution among Asian countries. Until now, more than 80 weed species have been reported from all over Asia (Table 15.1). The acquired data and the phylogenetic analysis reveal that phytoplasmas associated with weeds belong to major species '*Ca.* P. asteris' (AY, 16SrI), '*Ca.* P. aurantifolia' (PWB, 16SrII), '*Ca.* P. australasia' (PWB, 16SrII), '*Ca.* P. cynodontis' (BGWL, 16SrXIV), and '*Ca.* P. trifolii' (CP, 16SrVI) and '*Ca.* P. ziziphi' (EY, 16SrV). Among them, AY and BGWL phytoplasmas are abundant and widely distributed all over Asia. In India, '*Ca.* P. cynodontis' has been associated with grasses, whereas '*Ca.* P. asteris' is primarily associated with other weed species. Among reported weeds, *Parthenium hysterophorus* is a widely spread weed and reported hosting phytoplasma strains of '*Ca.* P. aurantifolia' and '*Ca.* P. australasia' (PWB, 16SrII). The phytoplasma strains of the PWB group are associated with crops like soybean (*Glycine max*), sesame (*Sesamum indicum*), French bean (*Phaseolus vulgaris*), papaya (*Carica papaya*), sugar beet (Beta vulgaris), marigold (*Calendula officinalis*), lettuce (*Lactuca sativa*), cauliflower (*Brassica oleracea*), black gram (*Vigna mungo*), mung bean (*Vigna radiata*), cow pea (*Vigna unguiculata*), tomato (*Solanum lycopersicum*), bamboo (*Dendrocalamus strictus*), and many others (Arocha et al., 2008; Reddy et al., 2014; Thorat et al., 2016; Verma et al., 2012; Yadav et al., 2015).

4. Management

The timely and precise identification of a plant disease is the critical factor for any disease management system. Preventive and phytosanitary measures applied at the initial stages of disease help successful management and check further disease spread. The easy-to-use equipment can be highly convenient to farmers, agronomists, and horticulturists. The techniques having high-throughput screening capacity will aid in monitor the transmission of phytoplasmas.

Weeds associated with phytoplasmas, which serves as reservoirs of the pathogen, needs to be managed with an integrated approach. The conventional way to control and mitigate weed infestation is manual pulling which is laborious and time-consuming, especially in larger fields. Therefore, many farmers rely on herbicides, which must be reconsidered due to the long-lasting harmful effects of chemicals residues. Many herbs develop resistance against chemical substances and become

Table 15.1 List of weed species reported from various Asian countries showing symptoms of phytoplasma diseases, their geographic distribution and taxonomic affiliation of the detected phytoplasma strain(s).

Weed host (botanical/ common name)	Disease Symptom(s)	Geographical location	'*Candidatus* Phytoplasma' (Group[a]/RFLP group[b])	GenBank Accession number	Reference
Acalypha indica (Indian copperleaf)	Little leaf	Lucknow/UP, India	'*Ca.* P. asteris' (AY/16SrI-B)	KX139546	Tiwari et al. (2017)
Achyranthes aspera (Latjeera)	Yellowing and little leaf	Lucknow/UP, India	'*Ca.* P. asteris' (AY/16SrI-B)	EU573926	Raj et al. (2009b)
Aegilops squarrosa (Goat grass)	Witches' broom, dwarfing	China	'*Ca.* P. asteris' (AY/16SrI-C)	NA	Wu et al. (2010)
Ageratum conyzoides (Billy goat-weed)	Leaf yellows, little leaf	Shahjahanpur/ UP, India	'*Ca.* P. asteris' (AY/16SrI)	JQ446367	Tiwari et al. (2012)
Amaranthus retroflexus (Redroot pigweed)	Reddening, dwarfing	Malatya, Turkey	'*Ca.* P. trifolii' (CP/16SrVI)	MT505687	Oksal (2020)
	Asymptomatic	Beijing, China	'*Ca.* P. ziziphi' (EY,16SrV-B)	HQ660580	Yang et al. (2011)
Amaranthus sp. (pigweed, Ramdana)	White leaf	Pantnagar/UK, India	'*Ca.* P. aurantifolia' (PWB/16SrII-A)	EU362627	Arocha et al. (2008)
Andrographis paniculata (creat, green Chirayta)	Witches' broom	Lucknow/UP, India	'*Ca.* P. australasia' (PWB, 16SrII-D)	KM359410	Saeed et al. (2015)
Arundo donax (Giant reed)	White, small leaves, stunting	Saudi Arabia	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	LT220881, LT220884	Omar (2016)
	Witches' broom, little leaf	Kushinagar/ UP, India	'*Ca.* P. asteris' (AY/16SrI-B)	KM985686	Tiwari et al. (2015)
Avena fatua (Wild oat)	Witches' broom, dwarfing	China	'*Ca.* P. asteris' (AY/16SrI-C)	NA	Wu et al. (2010)
Axonopus compressus (Broadleaf carpet grass)	White leaf	Songkhla University, Thailand	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	AB909429	Sunpapao (2016)
	Chlorosis	Singapore	'*Ca.* P. cynodontis' (BGWL, 16SrXIV)	EU234511	Koh et al. (2008)

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Barleria prionitis (Vajradanti)	Leaf yellowing, chlorosis and little leaf	New Delhi/ DL, India	'*Ca.* P. aurantifolia' (PWB/16SrII)	JF958127	Kumar et al. (2012a)
Bidens alba (Shepherd's needles)	Phyllody, virescence, witches' broom, and little leaf	Iran	'*Ca.* P. phoenicium' (PPWB, 16SrIX)	KY358007	Hemmati et al. (2017)
Brachiaria sp. (Brachiaria grass)	White leaf	Sri Lanka	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV-A)	MT862162	(UN)
		Thailand	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV-A)	AB052872	Jung et al. (2003)
Bupleurum falcatum (Chinese thorowax)	Dwarfing and yellowing	Yeongcheon, South Korea	'*Ca.* P. asteris' (AY/16SrI)	AB693129	Win et al. (2012)
Calotropis gigantea (crown flower)	Yellowing	Gorakhpur/UP, India	'*Ca.* P. trifolii' (CP/16SrVI)	HM485690	Priya et al. (2010)
Cannabis sativa (Industrial Hemp)	Witches' broom and yellowing	UP, India	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	KM220612	Mall et al. (2015)
Cannabis sativa (Industrial Hemp)	Yellowing, little leaf, and witches' broom	Dehradun/UK, India	'*Ca.* P. sacchari' (RYD, 16SrXI-B)	KX894735	Maurya et al. (2020)
	Little leaf and witches' broom	Kushinagar/ UP, India	'*Ca.* P. asteris' (AY/16SrI-)	KP768073	Nabi et al. (2015a)
	Witches' broom	Lakhimpur-Kheri/UP, India	'*Ca.* P. asteris' (AY/16SrI)	EU439257	Raj et al. (2008b)
		New Delhi/ DL, India	'*Ca.* P. trifolii' (CP/16SrVI-D)	MF509775	Taloh et al. (2020)
		China	'*Ca.* P. ziziphi' (EY,16SrV-B)	EF029092	Zhao et al. (2007)

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Cardaria draba (Whitetop)	Dwarfing, phyllody, witches' broom	Iran	ND	NA	Hosseini and Salehi (2011)
Cassia italica (Italian senna)	Witches' broom	Oman	'*Ca.* P. omanense' (16SrXXIX-A)	EF666051	Al-Saady et al. (2008)
Celosia argentea (Cock's comb)	Flat stem	Tripura, India	'*Ca.* P. asteris' (AY/16SrI-B)	MH547063	Rao et al. (2018)
Chenopodium album (Goosefoot, wild spinach)	Witches' broom	New Delhi/ DL, India	'*Ca.* P. australasia' (PWB, 16SrII-D)	MF040139	Taloh et al. (2020)
Chenopodium ambrosioides (Epazote)	Little leaf and fasciation	China	ND	JN836942	Li et al. (2012)
Chenopodium morale (Nettle-leaved goosefoot)	Yellowing and stunting	Saudi Arabia	'*Ca.* P. aurantifolia' (PWB/16SrII)	EU119389	Alhudaib et al. (2009)
Chrysanthemum indicum (Chrysanth)	Little leaf	New Delhi, Delhi	ND	JQ268257	Kumar et al. (2012b)
Chrysopogon aciculatus (Golden beard grass)	White leaf symptoms	Myanmar	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	AB642601	Win and Jung (2012)
Cleome viscosa (Tick weed)	Little leaf	Naldurg/MH, India	'*Ca.* P. australasia' (PWB/16SrII-D)	LT558784	Thorat et al. (2016)
Convolvulus arvensis (Field bindweed)	Yellowing and stunting	Saudi Arabia	'*Ca.* P. aurantifolia' (PWB/16SrII)	EU119391	Alhudaib et al. (2009)
	Witches' broom	Iran	'*Ca.* P. solani' (STOL, 16SrXII-A)	MG010135 MG010136	Salehi et al. (2018b)
Conyza canadensis (Canadian Horseweed)	Yellowing, witches' broom	Iran	'*Ca.* P. trifolii' (CP/16SrVI-A)	KT807471	Zibadoost and Rastgou (2016)

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Corchorus olitorius (Jute mallow)	Little leaf and bunchy top	Kolkata/WB, India	'*Ca.* P. asteris' (AY/16SrI)	KF501045	Biswas et al. (2014)
Crotalaria pallida (Smooth rattle pods)	Little leaf	Mysuru/KR, India	'*Ca.* P. australasia' (PWB/16SrII-D)	KX013260	Yadav et al. (2016)
Crotalaria spectabilis (Showy rattlebox)	Fasciation little leaf	New Delhi/ DL, India	'*Ca.* P. asteris' (AY/16SrI)	HM137557	Kumar et al. (2010)
Crotalaria tetragona (Eastern Rattlepod)	Witches' broom	Meghalaya/ AS, India	'*Ca.* P. asteris' (AY/16SrI)	FJ185141	Baiswar et al. (2010)
Croton bonplandianum (Ban Tulsi)	Witches' broom, little leaf, yellowing, virescence, and phyllody	Baramati/MH, India	'*Ca.* P. australasia' (PWB/16SrII-D)	MT555411 MT555412	Kirdat et al. (2020)
	Lethal yellows	Gorakhpur/UP, India	'*Ca.* P. trifolii' (CP/16SrVI)	KJ410527	
Cymbopogon citratus (Lemongrass)	White leaf	Manesar/DL, India	'*Ca.* P. australasia' (PWB, 16SrII-D)	KF773150	(UN)
Cynodon dactylon (Bermuda grass)	White, small leaves, stunting	Saudi Arabia	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	LT220876, LT220879	Omar (2016)
	White leaf, stunted growth	Gorakhpur/UP, India	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	KF760445	Rao et al. (2007)
	White leaf	Magway and Nyungoo, Myanmar	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	NA	Win et al. (2013)
Datura innoxia (Downy thorn-apple)	Little leaf	Ambedkar Nagar/UP, India	'*Ca.* P. trifolii' (CP/16SrVI)	EU573925	Raj et al. (2009a)

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Datura stramonium (Jimsonweed)	Little leaf, witches' broom	Gorakhpur/UP, India	'*Ca.* P. trifolii' 'CP/16SrVI'	KC468279	Singh et al. (2012)
Descurainia sophia (Flixweed tansy-mustard)	Witches' broom, dwarfing	China	'*Ca.* P. asteris' (AY/16SrI-C)	NA	Wu et al. (2010)
Dichanthium annulatum (Marvel grass)	White leaf	Gorakhpur/UP, India	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	FJ348654	Rao et al. (2009)
Digitaria ciliaris (Southern crabgrass)	Chlorotic leaf	UP, India	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	KJ661543	Mall et al. (2015)
Digitaria sanguinalis (Hairy crabgrass)	Little leaf	Gorakhpur/UP, India	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	GQ403689	Rao et al. (2010)
Dodonaea angustifolia (Sand olive shrub)	White, small leaves, stunting	Saudi Arabia	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	LT220882, LT220883	Omar (2016)
Echinochloa colonum (Jungle rice)	Yellows, dwarfing	India	ND	NA	Reddy and Jeyarajan (1988)
Eleusine indica (Goosegrass)	Chlorotic leaf	Kasargod/ Kerala, India	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	KJ661544	Mall et al. (2015)
	White leaf	Magway and Nyungoo, Myanmar	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	NA	Win et al. (2013)
Eragrostis cilianensis (Stink grass)	Witches' broom, dwarfing	China	'*Ca.* P. asteris' (AY/16SrI-C)	NA	Wu et al. (2010)
Erysimum cheiranthoides (Wormseed mustard)	Witches' broom, dwarfing	China	'*Ca.* P. asteris' (AY/16SrI-C)	NA	Wu et al. (2010)

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Foeniculum vulgare (Fennel)	Phyllody	Gujarat, India	'*Ca.* P. aurantifolia' (PWB/16SrII-C)	EF584107	Bhat et al. (2008)
Lithospermum arvense (Corn gromwell)	Witches' broom, dwarfing	China	'*Ca.* P. asteris' (AY/16SrI-C)	NA	Wu et al. (2010)
Melochia corchorifolia (Chocolate weed)	Witches' broom, virescence, and phyllody	China	'*Ca.* P. asteris' (AY/16SrI)	KX150461	Chen et al. (2017)
Mikania micrantha (Bitter vine, climbing hemp)	Yellowing and little leaf	Bangladesh	'*Ca.* P. asteris' (AY/16SrI)	EU921447	Kelly et al. (2009)
Mimosa pudica (Sensitive plant)	Leaf yellowing, little leaf, and witches' broom	Indonesia	'*Ca.* P. asteris' (AY/16SrI)	EU273883	Boa et al. (2010)
Mirabilis jalapa (Beauty of night)	Little leaf	New Delhi, Delhi	ND	JQ268255	Kumar et al. (2012b)
Ocimum canum (tulsi, Basil)	Little leaf	Gorakhpur/UP, India	'*Ca.* P. asteris' (AY/16SrI)	KX073966	Rao et al. (2017b)
Oplismenus burmannii (Burmann's basketgrass)	Cholorosis	UP, India	'*Ca.* P. aurantifolia' (PWB/16SrII)	KF760446	Mall et al. (2015)
	White leaf	Gorakhpur/UP, India	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	GQ403690	Rao et al. (2010)
Parthenium hysterophorus (Carrot or congress grass)	Witches' broom, phyllody, and virescence	China	'*Ca.* P. aurantifolia' (PWB, 16SrII-V)	KC953002	Cai et al. (2016)
		New Delhi/ DL, India	'*Ca.* P. aurantifolia' (PWB/16SrII)	KJ435302	(UN)
		China	ND	EU779826	Li et al. (2011)
		UP, India	'*Ca.* P. aurantifolia' (PWB/16SrII)	KJ676961	Mall et al. (2015)

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		Tirupati/AP, India	'*Ca.* P. aurantifolia' (PWB/16SrII-C)	KP899066	Naik et al. (2015)
		Lucknow/UP, India	'*Ca.* P. asteris' (AY/16SrI)	EU375485	Raj et al. (2008a)
		Mysuru/KR, India	ND (PWB/16SrII)	KC855731	(UN)
		New Delhi/ DL, India	'*Ca.* P. australasia' (PWB/16SrII-D)	MF040141	Taloh et al. (2020)
		Naldurg/MH, India	'*Ca.* P. aurantifolia' (PWB/16SrII-C)	LN879437 LN879438	Yadav et al. (2015)
		Pune/MH, India	'*Ca.* P. australasia' (PWB/16SrII-D)	LN879442	Yadav et al. (2015)
			'*Ca.* P. aurantifolia' (PWB/16SrII-C)	LN878982	Yadav et al. (2015)
Paspalum conjugatum (Buffalo grass)	Chlorosis	Singapore	'*Ca.* P. cynodontis' (BGWL, 16SrXIV)	EU234512	Koh et al. (2008)
Pedalium murex (Crow thorn, elephant caltrop)	Phyllody and little leaf	Kayamkulam/ KL, India	'*Ca.* P. australasia' (PWB/16SrII-D)	KJ584566	Babu et al. (2015)
Phalaris minor (Little seed canary grass)	Yellow leaf	Gorakhpur/UP, India	'*Ca.* P. asteris' (AY/16SrI)	KJ622368	(UN)
Phaseolus vulgaris (French bean)	Leaf yellowing, chlorosis, and little leaf	Pantnagar/UK, India	'*Ca.* P. aurantifolia' (PWB/16SrII)	EU362629	Arocha et al. (2008)
Phragmites australis (Tall reed)	Witches' broom, little leaf	China	'*Ca.* P. ulmi' (EY, 16SrV-B)	KC331052	Li et al. (2013)
Phyllanthus amarus (Shatter stone)	Yellows, little leaf, witches' broom	Lucknow/UP, India	ND	NA	Samad et al. (2004)

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Phyllanthus niruri (Stonebreaker)	Little leaf and leaf chlorosis	Gorakhpur/UP, India	'*Ca.* P. asteris' (AY/16SrI)	KM280566	Chaube et al. (2015)
Plantago lanceolata (Narrow leaf plantain)	Yellowing and stunting	Saudi Arabia	'*Ca.* P. aurantifolia' (PWB/16SrII)	EU119398	Alhudaib et al. (2009)
Pluchea indica (Indian camphorweed)	Witches' broom	Lucknow/UP, India	'*Ca.* P. ziziphi' (EY/16SrV)	KC778402	(UN)
Polygala mascatense (Milkwort or snakeroots)	Little leaf, witches' broom, and phyllody	Oman	ND	NA	Livingston et al. (2006)
Portulaca grandiflora (Moss rose)	Little leaf, stunting, yellowing, and witches' broom	India	ND	NA	Ajayakumar et al. (2007)
Praxelis clematidea (Praxelis)	Phyllody	Hainan, China	'*Ca.* P. australasia' (PWB, 16SrII-V)	KY568717	Yang et al. (2017)
Prosopis farcta (Syrian mesquite)	Witches' broom	Iran	ND	NA	Hosseini and Salehi (2011)
Ranunculus sceleratus (Celery-leaved buttercup)	Little leaf	Gorakhpur/UP, India	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	KF188427	Singh et al. (2013)
Scaevola taccada (Beach naupaka)	Witches' broom	Oman	'*Ca.* P. aurantifolia' (PWB/16SrII)	AB257291	Al-Zadjali et al. (2012)
Sclerocarpus africanus (African bonebract)	Little leaf and witches' broom	Gorakhpur/UP, India	'*Ca.* P. asteris' (AY/16SrI-B)	KJ561783	Nabi et al. (2015b)
Setaria palmifolia (Palm grass)	Yellows, little leaf,	Tripura, India	'*Ca.* P. cynodontis' (BGWL/ 16SrXIV)	MH551478	Rao et al. (2018)

Continued

Table 15.1 List of weed species reported from various Asian countries showing symptoms of phytoplasma diseases, their geographic distribution and taxonomic affiliation of the detected phytoplasma strain(s).—cont'd

Weed host (botanical/ common name)	Disease Symptom(s)	Geographical location	'*Candidatus* Phytoplasma' (Group[a]/RFLP group[b])	GenBank Accession number	Reference
Setaria verticillate (Bristly foxtail)	Little leaf and chlorosis	Gorakhpur, UP	'*Ca.* P. australasia' (PWB, 16SrII-D)	MK673993	Mall et al. (2020)
Sonchus oleraceus (Common sow thistle)	Phyllody	Iran	'*Ca.* P. asteris' (AY/16SrI-B)	MG652627	Salehi et al. (2018a)
Sophora alopecuroides (Bitter bean)	Yellowing, little leaf and stunting	Iran	'*Ca.* P. solani' (STOL, 16SrXII-A)	KF263685, KF374706	Allahverdi et al. (2014)
			'*Ca.* P. australasia' (PWB, 16SrII-D)	MN219989	Hosseini et al. (2020)
	Dwarfing and yellowing	Iran	'*Ca.* P. omanense' (16SrXXIX-A)	MN219986	Hosseini et al. (2020)
	Yellowing, little leaf, stunting	Iran	'*Ca.* P. trifolii' (CP/16SrVI-D)	KT807470	Zibadoost and Rastgou (2016)
Sorghum halepense (Johnson grass)	Yellowing, Witches' broom	Iran	'*Ca.* P. trifolii' (CP/16SrVI-A)	KT807469	Zibadoost and Rastgou (2016)
Stachytarpheta jamaicensis (Blue snakeweed)	Witches' broom	Bengaluru/ KR, India	ND	NA	Pallavi et al. (2011)
	Phyllody	India	'*Ca.* P. aurantifolia' (PWB/16SrII-C)	MK603205	Pramesh et al. (2020)
Tephrosia purpurea (Wild Indigo)	Witches' broom	Pune/MH, India	'*Ca.* P. aurantifolia' (PWB/16SrII-C)	LN878981	Thorat et al. (2016)
			'*Ca.* P. aurantifolia' (PWB/16SrII-M)	HG792252	Yadav et al. (2014)
Trichodesma zeylanicum (Camel or cattle bush)	Little leaf	Solapur/MH, India	'*Ca.* P. aurantifolia' (PWB/16SrII-C)	LT558789	Thorat et al. (2016)
Trifolium repens (White clover)	Witches' broom, dwarfing	China	'*Ca.* P. asteris' (AY/16SrI-C)	NA	Wu et al. (2010)

Table 15.1 List of weed species reported from various Asian countries showing symptoms of phytoplasma diseases, their geographic distribution and taxonomic affiliation of the detected phytoplasma strain(s).—cont'd

Weed host (botanical/ common name)	Disease Symptom(s)	Geographical location	'*Candidatus* Phytoplasma' (Group[a]/RFLP group[b])	GenBank Accession number	Reference
Tylophora indica (Antamul)	Little leaf	Manesar/DL, India	'*Ca.* P. australasia' (PWB/16SrII-D)	KF773149	(UN)
Urochloa distachya (Signal Grass)	White leaf	Alappuzha/ KL, India	'*Ca.* P. cynodontis' (BWL/16SrXIV-A)	KJ873877	Babu et al. (2014)
Veronica didyma (Veronica)	Witches' broom, dwarfing	China	'*Ca.* P. asteris' (AY/16SrI-C)	NA	Wu et al. (2010)

AY, aster yellows; BGWL, Bermuda grass white leaf; CP, clover proliferation; EY, elm Yellows; ND, Not determined; PPWB, pigeon pea witches' broom; PWB, peanut witches' broom; RYD, rice yellow dwarf; STOL, 'stolbur'; UN, Unpublished.
[a]The group name is based on the disease symptoms shown by the host plant (Lee et al., 1998); Many reported sequences are short in length to determine the RFLP group/subgroup (Zhao et al., 2009) or to determine the 'Candidatus' species (IRPCM, 2004).
[b]The species name, RFLP group/subgroup listed here, are reported from the cited publication, not determined by the authors.

challenging to control. Concerning this, various alternative tactics need to be adopted for sustainable agriculture. Preventive weed management practices aim to use high-quality weed-free seeds, farming equipment; screening irrigation waters for weed seed transportation; use of completely decomposed compost and manure to prevent seed germination. Cultural weed control aims at making fields less favorable to non−crop plants with planting high-adaptive and competitive species; shallow seeding (thus, crops can grow faster than other herbs). Mechanical weed control involves ploughing, tilling, mowing, manual pulling (hand removal), burning, mulching to ensure the eradication of unwanted plants (Harker and O'Donovan, 2013; Shahzad et al., 2021). Insect vector control using an insecticide is conventionally being used; however, it may not stop the appearance of symptoms as pathogen transmission occurs faster than the action of insecticide. Optimally timed and dose-controlled insecticide use can reduce intracrop transmission and check the development of resistance by surviving population (Weintraub, 2007).

Bioagents like arbuscular mycorrhiza are reported to reduce disease and degeneration of phytoplasma cells (Lingua et al., 2002). Developing cultivars resistant to either phytoplasmas or their insect vectors is compelling. The development of plant varieties with suitable agronomic properties is a safe, effective, and environmentally friendly option in the long-term perspective.

5. Conclusion

More than 80 weed species reported to host phytoplasmas from all over Asia, among which 30 are reported from India. The data collected in this review and molecular analysis have shown that weed-

infecting phytoplasmas mainly belong to '*Ca.* P. aurantifolia', '*Ca.* P. australasia', '*Ca.* P. cynodontis', and '*Ca.* P. trifolii' and '*Ca.* P. ziziphi' (PWB, 16SrII; EY, 16SrV; CP, 16SrVI; and BGWL, 16SrXIV). The AY, PWB, and BGWL phytoplasmas have a wider occurrence all over Asia. Phytoplasma transmitted from weeds reduce the crop yield and marketing parameters leading to extensive yield losses. The conventional disease control measure like the use of seeds free from contamination of weed seeds, eradication of the weeds around the field, timely removal of infected crop plants, rotation with the non−host plant should result in the containment of disease spread along with the integrated management practices including the development of resistant varieties for a sustainable agriculture.

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