



REVIEW ARTICLE

# Comprehensive review on sesame phyllody, genetic diversity, symptom expression, vectors and management strategies

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## Abstract

Insect pests and diseases are the major biotic stresses to crop plants. Some are highly dreadful and cause yield loss even up to 100 %. Sesame crop face a serious problem worldwide due to the insect vector-transmitted phytoplasma disease called phyllody. The transmission was facilitated by various leafhoppers (Cicadellidae: Hemiptera). The predominant phytoplasma group infecting the sesame crop is 16SrI and 16SrII in most of the sesame-growing countries. The phytoplasma subgroup 16SrII-D is the most common one in India, Oman, the Republic of Korea, Thailand and Turkey. The leafhopper species, *Orosius albicinctus* vectoring the transmission is replaced with the species *Hishimonas phycitis*, which is the dominant one in the sesame ecosystem in terms of population and transmission (88.33 %) of the disease. In most of the sesame-growing countries, the symptoms expressed in phytoplasma infected sesame plants are yellowing, virescence, shoot apex fasciation, floral sterility, change in flower color and cracking of capsules. Diversity in the symptoms expression is due to the changes in host plant anatomy, biochemical and physiological changes and variations in the enzymes and phytohormones levels. The effector protein SAP54 is mainly responsible for inducing the phyllody symptoms in phytoplasma infected plants. Since phytoplasma is an obligate pathogen, direct management methods may not be feasible. Targeting the vector population with an integrated pest management strategy would reduce the disease incidence and improve the yield parameters of the sesame crop. In this review, the progress made so far in understanding the phytoplasma infection in sesame, different groups and subgroups of phytoplasma, the diverse symptoms observed in different geographical locations and the management practices followed are discussed comprehensively.

**Keywords:** effector protein; *Hishimonas phycitis*; polysepalous calyx; phytoplasma subgroup; SAP54; vivipary

## Introduction

Sesame (*Sesamum indicum* L.) plays an important role in the oilseed economy throughout the world due to its status as one of the important edible annual groups of oilseed crops. Also, it is an ancient and the first oilseed crop used by human civilization (1–4). Sesame is an annual warm season crop primarily adapted to areas with well-drained soils (5). It is mainly cultivated for its seeds, which has an oil content of around 55 %. Sesame oil has excellent quality maintenance due to its natural antioxidants sesamol, sesamin and sesamol. In addition, sesame seeds contain protein (20 %), oleic acid (47 %) and linolenic acid (39 %) (6–9). China, India and Myanmar are the world's largest producers of sesame (8). India is contributing the maximum production of sesame in the world, with a production of

7.84 lakh tonnes from 17.14 lakh hectares and a productivity of 457 kg ha<sup>-1</sup>(10). Most of the states in India cultivate sesame crops for three seasons in a year viz. *Rabi* (October to December) or Summer (February to May) and *Kharif* (June to September) (10, 11, 4). Worldwide, the major constraints in sesame production are a narrow genetic base, low harvest index, susceptibility to insect pests and diseases, seed shattering and indeterminate growth (3, 4). Another major problem in the sesame crop is the vector-borne phytoplasma diseases commonly referred to as Phyllody in many areas of sesame cultivation in the world (3, 4, 12–15) and the related symptoms were a. Witches' broom, b. Polysepalous calyx, c. Shoot like structure of ovary, d. Ovo-vivipary, e. Phyllody, f-g. Auxiliary shoot growth, h. Floral sterility, i. Floral virescence, j. Shoot apex fasciation,

k. Cracking of capsule and l. Seed germination in capsule (Fig. 1). The incidence of phytoplasma disease varies from year to year and its incidence is minor in most of the growing areas and major in many countries like India and Egypt. For instance, the incidence was reported to be as high as 100 % in India and 90 % in Burma (16). In India, one of the top ten sesame-producing countries globally, the incidence of sesame phyllody disease ranges from 10 %-100 % (17-19). In light of this, comprehensive narrative was provided about the sesame phytoplasma causing different symptoms in sesame, the genetic diversity of the phytoplasma with group and subgroup levels with reference to different geographical conditions, different leafhopper species transmitting the sesame phytoplasma and the dominant one in transmitting the sesame phyllody and its management strategies.

### Sesame phytoplasma and its distribution

Phytoplasma belongs to the class mollicutes, which are cell wall-less, pleomorphic, unculturable prokaryotes, reside in the plant phloem, feed on the plant nutrients for survival, very small in genome size (500-1350 Kbp) and an AT-rich genome (20). Phytoplasma move within the plants through the phloem from source to sink and they can pass through sieve elements. Since phytoplasma is a sieve element-inhabiting pathogen, it spread in nature by sap-sucking leafhoppers, plant hoppers and psyllids (21, 22). According to earlier studies, phytoplasma-associated phyllody disease was first detected in Pakistan in 1908 and in Burma during 1924 and later in India (23-25). For a long time, phyllody has been considered a viral-associated plant pathology (26). Later, many researchers have reported phyllody disease associated with phytoplasma infection and transmitted by insect vector leafhoppers belongs to the Cicadellidae family in the order Hemiptera (17, 21, 27, 28).

Sesame phyllody is a very serious phytoplasma disease limiting the yield potential of sesame in sesame growing regions and dramatically decreasing sesame yields, especially in warm climates. Sesame phyllody may cause up to 80 % seed yield loss (29, 30). In Egypt, sesame seed and oil yields were drastically reduced due to phyllody (31). The disease has now spread and been observed in all sesame-growing regions of the world. Till 2009, phytoplasma infection in sesame has been reported in India, Iran, Iraq, Israel, China, Myanmar, Pakistan, Thailand, Sudan, Egypt, Nigeria, Oman, Tanzania, Ethiopia, Turkey, Uganda, Upper Volta and Mexico (29). The list was then extended to Syria, the Mediterranean environment,

Paraguay, Venezuela and Burkina Faso (8, 32, 33).

### Diversity in phytoplasma disease symptom expression in sesame

Plants infected with any phytopathogens or vector-borne pathogens express more than one symptom. For instance, symptoms of vector borne virus disease are expressed as yellowing of leaf in black gram and vein clearing and yellowing in okra and cotton. In contrast, the phytoplasma infection in sesame vectored by the leafhoppers showed a range of symptoms from yellowing to seed germination in capsule or ovo-vivipary. The diversity of symptom expression of phytoplasma infection in sesame is yellowing, phyllody, witches' broom, shoot apex fasciation, floral sterility, polysepalous calyx and shoot-like structure of the ovary, proliferation, cracking of the capsule, ovo-vivipary and germination of the seed in the capsule (Fig. 1) (8, 35, 36). Similarly, we observed different kinds of symptom expression in phytoplasma infected sesame plants in sesame at the Regional Research Station, Vriddhachalam, Tamil Nadu and India (Fig. 1), which is one of the main centers of All-India Co-ordinated Research Project on Sesame. So far, the center has released six sesame varieties, including four black seeded (VRI1, VRI2, VRI4 and VRI6) and two white seeded varieties (VRI3 and VRI5). Besides, other sesame varieties like Co-1, SVPR-1, Paiyur-1, TMV-4 and TMV-7 are also cultivated in Tamil Nadu. Different symptoms were observed due to phytoplasma infection in sesame varieties during the cropping season, as presented in Fig. 1. Different symptoms were observed in the phytoplasma infected sesame irrespective of the geographical location and varieties, including wild species in the north eastern states and sesame species, including wild in southern states of India and in the Mediterranean environment (3, 4, 33, 35). The sesame phytoplasma disease is also termed as "green flowering disease" or "Pothe" in Burma, "Sepaloidy" and "Stenosis" in India and "Phyllomania" or "Green flowering" in Africa (29). Phytoplasma-induced negative impacts also include stomatal closure, photosynthetic impairment due to declining leaf area and photosynthetic pigments, leading to limited transport of photo-assimilates to sink organs, causing yield and quality loss (37-39). Phytoplasma-infected plants showed reduced water content, chlorophyll content, growth and yield components resulting in 37.9 % and 42.5 % reduction in seed and oil yield respectively (31). This might be due to the changes in anatomical, morphological and physiological changes in phytohormonal levels in phytoplasma infected sesame plants (40).

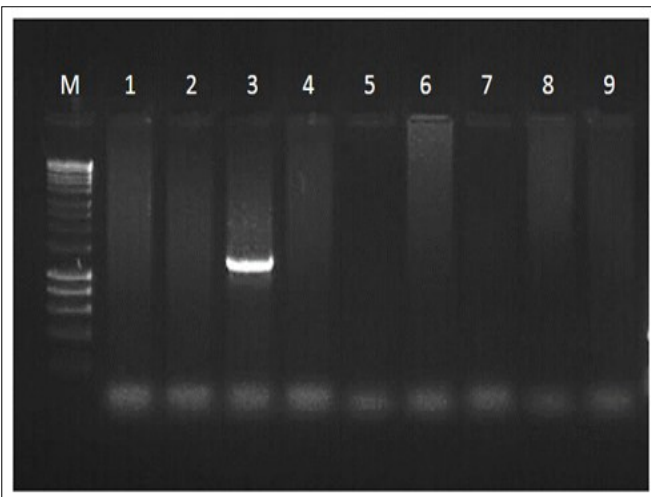


**Fig. 1.** Diversity of symptom expression in sesame due to phytoplasma infection.

a. Witches' broom, b. Polysepalous calyx, c. Shoot-like structure of ovary, d. Ovo-vivipary, e. Phyllody, f-g. Auxiliary shoot growth, h. Floral sterility, i. Floral virescence, j. Shoot apex fasciation, k. Cracking of capsule, l. Seed germination in a capsule

### Insect vectored phytoplasma transmission

In general, the phytoplasma disease in sesame is transmitted by three modes viz. vegetative propagation such as grafting, dodder and insect vectors like leafhopper (35, 41). The latter one is the major and common factor and prevalent in sesame-growing areas worldwide. Since the deliberate attempt (grafting) may not be done with the scion from infected plants and it may give an idea about one of the modes of phytoplasma transmission. The next mode is through the dodder weeds which is also not a common one. The phytoplasma is not transmitted through seeds of the previous generation since, the seeds collected from infected plants and sown in the next season did not show any typical symptoms of phytoplasma infection under insect proof cage conditions (42). Absence of phytoplasma in sesame plants raised from seeds collected from phytoplasma infected plants and also in the seeds collected from the infected plants confirmed that the transmission may not occur through seeds (Fig. 2). Hence, the only effective mode of transmission is by leafhoppers. The leafhoppers feed in the phloem of infected plants and acquire phytoplasmas passively which accumulate in acinar cells of the salivary gland from which they are transmitted to healthy plants (21, 36).



**Fig. 2.** Phytoplasma was absent in all the samples when tested with universal primers P1/P7 and R16F2n/R16R2. The phytoplasma was present in the positive control (sesame phytoplasma) at an amplicon size of 1250 bp.

M- Molecular marker (1kb); 1- Sesame plant raised from healthy seeds; 2- Sesame plant raised from seeds of phyllody infected plant; 3- Positive control (Sesame phytoplasma); 4-6- Seeds collected from phyllody infected plants; 7-9 Miridbug from phyllody infected sesame plant.

Different groups and subgroups of phytoplasma causing phyllody in sesame are transmitted by various leafhopper species (43). Leafhopper species viz. *Neoliturus haematoceps* and *Circulifer haematoceps* from Iran and Turkey, *Orosius orientalis* from Iran, Pakistan, Turkey and India were reported as vectors of sesame phyllody phytoplasma (15, 29, 43-46). The leafhopper samples from sesame fields of the Tamil Nadu region of India belong to more than five different species. Samples collected during *rabi*/summer season belong to two different species (48). *Kharif* season leafhopper specimens were identified as *Orosius albicinctus*, *Hishimonas phycitis*, *Exitianus* spp., *Thomsonia porrecta*, *Balclutha* sp. and *Serriana jaina* (Fig. 3). Whereas *rabi*/summer season samples were identified as *O. albicinctus* and *H. phycitis*. Recently confirmed that the phytoplasma present in the vector *Exitianus indicus* and its host plant sesame is closely related to aster yellows phytoplasma in Assam, India (49). In line with the findings, it showed that the dominant species in sesame ecosystem in both the season were *O. albicinctus* and *H. phycitis* (Fig. 4) (49). Among the six species identified two species viz. *O. albicinctus* and *H. Phycitis* well proven for their role as a vector in sesame ecosystem in India (27, 35, 36, 41, 49, 54). Recently it was observed that the population of *H. phycitis* dominated the *O. abicinctus* in Tamil Nadu, India (Fig. 4-5). Whereas in Iran, Pakistan, Turkey and Thailand it is vectored by *Neoliturus haematoceps* (13-15, 46). Most recently, the third one *Exitianus indicus* also confirmed for its vector role in phytoplasma transmission (49). Since the other leafhopper *Cofana unimaculata* collected from the same location showed the absence of phytoplasma (49). Also, among the four leafhopper species viz. *H. phycitis*, *E. indicus*, *C unimaculata* and *Nephotettix nigropictus*, only *H. phycitis* transmitted the disease about 88.33 % (36). *H. phycitis* leafhopper was also reported as a natural vector of phytoplasma associated with brinjal little leaf in India and the phytoplasma transmitted belonged to 16SrVI-D subgroup (50). In contrast, in Mediterranean Turkey the phytoplasma groups reported were 16SrII-D, 16SrVI-A and 16SrIX-C (51).

The role of yet another three species as vector in sesame field needs to be investigated further. Besides, a greater number of mirid bug, *Nesidiocoris* sp. and *Compolyomma levidis* also seen in sesame ecosystem in phyllody infected plants. On an average, 10-15 bugs from a plant for single tapping were recorded. Since, the mirid bugs also feed on the sap from phloem vessels, they may also be responsible for transmitting the phytoplasma diseases in sesame. This line warrants the further research and confirmation with transmission studies. However, mirid bugs collected from phyllody infected plants were subjected to PCR amplification using phytoplasma universal primers which showed no amplification (Fig.

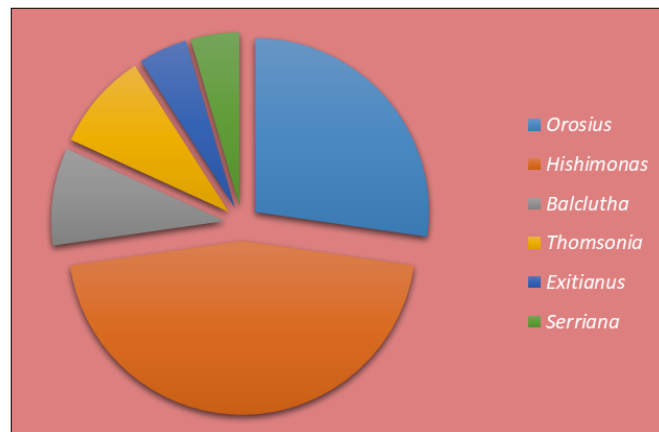


**Fig. 3.** Leafhopper species identified in Tamil Nadu, India from the sesame field: 1. *Orosius albicinctus*, 2. *Hishimonas phycitis*, 3. *Balclutha* sp., 4. *Thomsonia porrecta* and 5. *Exitianus* sp.

2). Further, it could be explained that the phytoplasma must penetrate specific cells of the salivary glands and high levels must accumulate in the posterior acinar cells of the salivary gland before they can be transmitted. At each point in this process, should the phytoplasmas fail to enter or exit a tissue, the insect would become a dead-end host and would be unable to transmit the phytoplasmas. Earlier studies showed that in the salivary glands, there are three barriers that pathogens must traverse before they can be ejected with the saliva: the basal lamina, the basal plasmalemma and the apical plasmalemma (52). Leafhoppers can be infected with phytoplasma and yet be unable to transmit it to healthy plants, which may be because of the salivary gland barriers (21). The vector, *H. phycitidis* requires 7 days to acquire pathogens and 30 minutes of inoculation feeding period. After 25-38 days phytoplasma disease symptoms were expressed in the healthy plants with 83.33 % transmission (36). Therefore, vector screening is a fundamental step in the development of management strategies for this disease. Hence, to manage this dreadful insect borne disease in sesame ecosystem curtailing the vector population is the prime most important task.

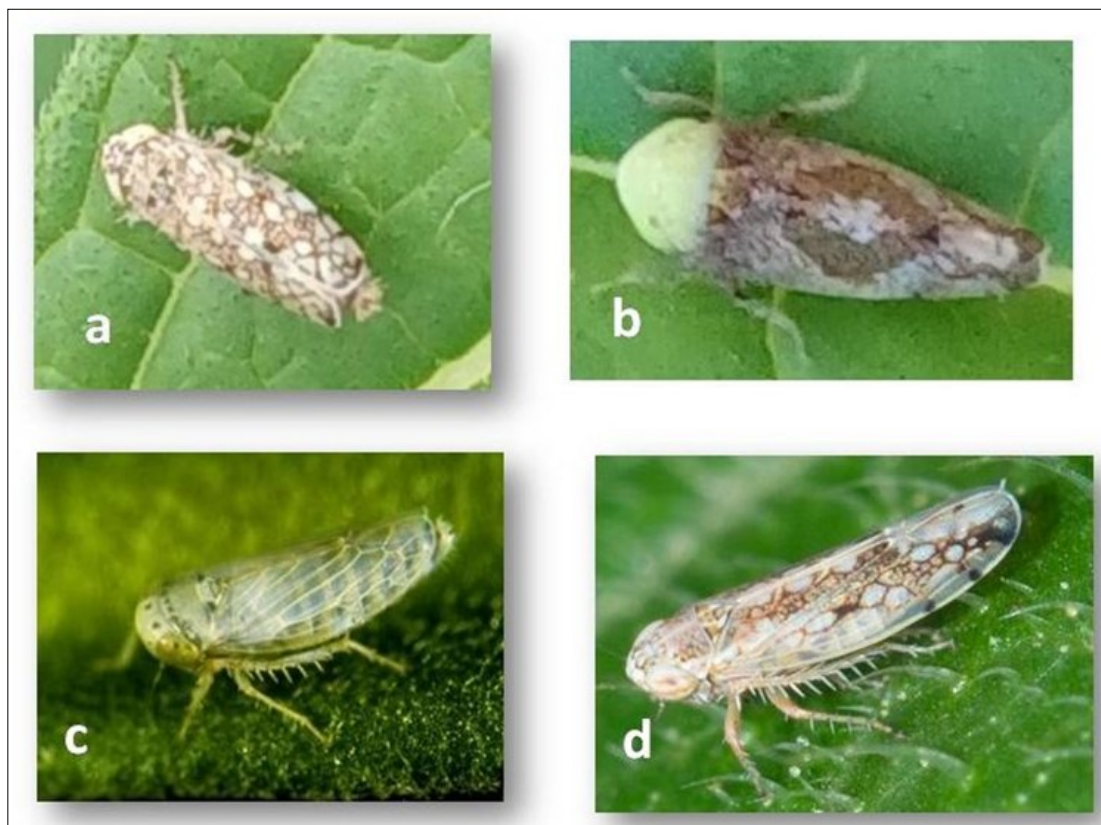
#### Genetic diversity of phytoplasma infecting sesame

Phytoplasma is transmitted by the insect vector leafhoppers which belong to the family Cicadellidae. Phytoplasma infecting crop plants belong to different groups from 16SrI to 16SrXII groups (21, 53). The phytoplasma infecting sesame comes under different group and subgroups in different geographical locations of the world. In India, group level (16SrI group) confirmation of phytoplasma associated with sesame phyllody was reported (54, 50). Among the different groups, the 16SrI group of phytoplasmas is the most important and has been associated with several phytoplasma diseases of crop plants in India (8). The 16SrI group of phytoplasma was identified in diseases like, sandal spike, periwinkle, sugarcane leaf yellows, Brachycome little leaf and Petunia flattened stem phytoplasma in



**Fig. 5.** Relative proportion of *Hishimonas* along with other leafhopper species in sesame ecosystem.

India (8, 50, 54, 55). However, 16SrII-C subgroup phytoplasma has not been reported to date from any of the plant species in India (3, 4, 8). As per the reports, the phytoplasmas associated with sesame phyllody and witches broom from Delhi, Uttar Pradesh and Bihar in India belong to *Candidatus* Phytoplasma *asteris* (16SrI) and *Candidatus* Phytoplasma *aurantifolia* (16SrII) groups (41). Phyllody infected sesame samples from different districts of Tamil Nadu show 98 % similarity with *Candidatus* phytoplasma *Australasia* (16SrII-D) (Cuddalore and Salem District) and sesame phyllody plants from Namakkal, Coimbatore, Thiruvannamalai and Villupuram districts showed 94.87 % to 98.28 % similarity with the 16SrII-B sub-group (18). Furthermore, earlier studies reported that phytoplasma associated with sesame species in India belonged to 16SrI-B and 16SrII-D (3). Phytoplasma associated with sesame exhibiting phyllody, witches broom and virescence were characterized molecularly and found that it belonged to 16SrI-B in Myanmar, 16SrII-A in Thailand, 16SrII-D in Oman and India, 16SrIV-C in Iran and 16SrVI-A and 16Sr-IX in Turkey, 16SrII-D and 16SrII-A in Taiwan, which were similar to the sub-group found in India and Thailand respectively.



**Fig. 4.** Dominant and most commonly found leafhopper species in sesame ecosystem in India (a & b) and other countries (c & d).

Phytoplasma group, 16Srl is commonly found in India, the Republic of Korea and Paraguay. Whereas, group 16SrlII is found in India, Oman, Pakistan, Taiwan, Thailand and Turkey (Table 1) and group 16SrlX is common in Turkey and Iran. It could be inferred that the majority of the sesame growing countries are commonly infected by the phytoplasma group, 16SrlII. Earlier studies reported that most of the Indian sesame species including *Sesame indicum*, *S. alatum*, *S. malabaricum*, *S. mulayanam* and *S. laciniatum* and *S. prostratum* were susceptible to phytoplasma belonging to the groups, 16Srl and 16SrlII (3). The cultivated species *S. indicum* showed the phytoplasma subgroup 16Srl-B and all the remaining wild species showed 16SrlII-D subgroup. Out of five wild species of sesame, the native Indian species, *S. laciniatum* and *S. prostratum* are on the verge of extinction due to their high susceptibility to phytoplasma infection. Also, the species, *S. prostratum* is found in Sri Lanka (3).

### Effect of phytoplasma infection on sesame plant growth and development

Symptoms of diseased plants may vary with the phytoplasma groups, host plant, stage of the disease, age of the plant at the time of infection and environmental conditions. Increased levels of the primary and secondary metabolites were recorded in phytoplasma infected plants compared to the healthy plants. Moreover, phytoplasma-infected plants showed drastic reductions in water content, chlorophyll content, growth and yield components, resulting in 37.9% and 42.5% reductions in seed and oil yield, respectively. Increased peroxidase value of oil from infested plants showed shorter shelf-life than the oil obtained from the healthy crop. Earlier studies reported the changes in anatomical/morphological features, morpho-physiological responses, stem anatomical structures and enzyme and phytohormone activities (31). Changes in the above-mentioned parameters due to phytoplasma infection in sesame are summarized in Table 2. Increased primary and secondary metabolites, phenolic content, soluble proteins, flavonoids, total tannins, alkaloids and defense enzymes indicate the induced systemic resistance reaction of the crop plant against the pathogen (40).

With respect to different kinds of symptoms expressed by the phytoplasma-infected sesame plants, changes in the level of phytohormones may play a vital role. For instance, an increase in the amount of cytokinin's may delay senescence, also lead to a competitive interaction between the source (leaves) and the sink (pods and seeds) or even cause excessive branching using apical dominance (40, 60, 61). This might be the underlying process or mechanism of the phytoplasma infected sesame plants to express the different symptoms like little leaf and witches broom. Other phytohormones like gibberellic acid (GA) and abscisic acid (ABA) are also the deciding factors for the type of symptom expressed in the affected plants (40). The increased GA content in the phytoplasma

infected plants might be the reason for the cracking of the seed capsule and seed germination in capsules, since GA regulates the seed dormancy and seed germination in crop plants. ABA is responsible for distinctive symptom expression like phyllody, shoot multiplication, internode shortening and small leaves and blooms.

### Effectors and symptom expression

It has been reported that SAP54, an effector protein secreted by phytoplasmas induces phyllody (62). The effector protein may act as a virulence factor of phytoplasma and may contribute to the down-regulation of auxin-responsive genes and affecting plant reproduction by perturbation of phytohormone signaling in sesame like TENGU in Onion, which induce dwarfism and witches' broom by inhibition of auxin related pathways (62, 63). The effector protein SAP54 induced severely altered flower morphology when expressed in the model plant, *Arabidopsis*. It results in abnormal leaf like flowers, typical of symptoms of phyllody and virescence that are characteristic symptoms of aster yellow witches' broom infection (62).

### Weed host of phyllody causing phytoplasmas

It has been reported that phytoplasma can affect more than 600 different plant species including weeds. Common weeds found in the sesame ecosystem are *Cleome viscosa*, *Amaranthus* spp., *Ammannia pacifera*, *Boerhavia diffusa*, *Commelina benghalensis*, *Cyperus rotundus* and *Tridax procumbens*. For instance, in Tamil Nadu, Asian spider flower or tick weed, *Cleome viscosa* is the major and common weed in the sesame ecosystem harbouring phytoplasma and exhibiting phyllody symptoms in both *kharif* and *rabi*/summer seasons. Whereas in Madhya Pradesh, Indian carrot grass/ *Parthenium hysterophorus* is the major weed in the sesame field and serves as a weed host for phytoplasma. Phytoplasma infection in these weed species during off-season and cropping season is quite common and serves as a source of inoculum for insect vectors. In Assam, India weed species like *Solanum torvum*, *Datura stramonium*, *Linum usitatissimum*, *Crotalaria juncea*, *Myosotis* spp., *Gerbera jamesonii*, *Ageratum* spp. and *Saccharum officinarum* exhibited phytoplasma infection (49). We have observed the phytoplasma disease infection and symptom expression in *Cleome viscosa*, *Phyllanthus niruri*, *Crotalaria juncea* and *Parthineium hysterophorus* at farmers' fields in Tamil Nadu (Fig. 6). These weed species may serve as collateral weed hosts for phytoplasma during off-season. Among the four weed species, *C. viscosa* is the major weed flora expressing phyllody symptoms throughout the year. Earlier studies revealed that *Croton* spp., *Parthenium hysterophorus* and *Crotalaria juncea* served as a weed host in southern states of India (4). In India, *Sclerocarpus africanus* and *Cannabis sativa* have been reported as natural hosts of sesame phyllody disease (41). However, reports about the weed host for sesame phytoplasma in other sesame growing countries are not available or not reported so far.

**Table 1.** Genetic diversity of phytoplasma group and subgroups

SN	Country	Phytoplasma group	Phytoplasma subgroup	Reference
1.	India	16Srl and 16SrlII	16Srl-B and 16SrlII-D 16Srl-M and 16SrlII-C	(29, 3) (56)
2.	Iran	16SrlII and 16SrlX	16SrlII and 16SrlX	(44, 45)
3.	Oman and Pakistan	16SrlII	16SrlII-D	(29)
4.	Thailand	16SrlII	16SrlII-A	(57, 58)
5.	Turkey	16SrlII, 16SrlVI, 16SrlX	16SrlII-D, 16SrlVI-A and 16SrlX-C	(12-15)
6.	Paraguay	16Srl	16Srl-B	(34, 59)

**Table 2.** Impact of phytoplasma infection on sesame plant growth, development, enzymes and phytohormones

SN	I. Parameter	Infected plant	Reference
1.	Primary metabolites		
2.	Secondary metabolites		
3.	Total soluble proteins		
4.	Total phenolic content		
5.	Total flavonoid content	Increased	(31)
6.	Total tannins		
7.	Total alkaloids		
8.	Water content		
9.	Chlorophyll content		
10.	Growth		
11.	Yield components		
<b>II. Anatomy/morphological features</b>			
1.	Leaf blade thickness	Decreased	
2.	Spongy tissue		
3.	Polysade tissue		
4.	Leafmidvein - width and length		(31)
5.	Vascular bundle -width and length	Increased	
6.	Phloem and xylem zone thickness		
<b>III. Morpho-physiological responses</b>			
1.	Main stem height		
2.	1st-order branches number plant		
3.	Leaves number plant		
4.	Main stem diameter	Decreased	
5.	Leaf area per plant		
6.	Plant dry weight		
7.	Leaf greenness index		(40)
8.	Relative water content		
1.	Stem diameter		
2.	Cortex thickness		
3.	Number of cortex layers		
4.	Vascular cylinder thickness	Increased	
5.	Vascular tissues thickness		(40)
6.	Phloem zone thickness		
7.	Xylem zone thickness		
8.	Pith diameter		
<b>IV. Enzyme activity</b>			
1.	Peroxidase (PO)		(40)
2.	Polyphenol Oxidase (PPO)	Increased	
<b>V. Plant growth regulators</b>			
1.	Auxin (IAA)		
2.	Cytokinin	Increased	
3.	Gibberellin (GA)		(40)
4.	Abscisic acid (ABA)	Decreased	



**a. Cleome viscosa**

**b. Phyllanthus niruri**

**c. Crotalaria juncea**

**d. Parthenium hysterophorus**

**Fig. 6.** Phytoplasma disease symptom in different weed hosts in sesame ecosystem.

## Sesame phytoplasma disease management

Despite the availability of literature of the phytoplasma causing phyllody disease in sesame, its insect vector, genetic diversity of the phytoplasma groups and its sub-group levels, management of this dreadful disease is a very big challenge in sesame ecosystem. Though, culturing of phytoplasma in on artificial media under *in vitro* conditions is difficult, the first and foremost thing considered for managing the phytoplasma disease in sesame is the weed host and insect vector. Hence, the holistic approaches comprising all the management strategies including cultural, mechanical, host plant resistance, botanical and chemical methods may provide an effective control against this dreadful disease.

### Proactive/Prophylactic measures

Prophylactic measures such as seed treatment with imidacloprid @ (6 g/kg) followed by spraying of imidacloprid (2 mL/10 L) or thiamethoxam (2 g/10 L) or clothianidin (0.5 g/L) substantially reduced the incidence of insect vector (leafhopper) and phyllody infection (64). Seed treatment with imidacloprid 17.8 SL @ 5 mL/kg + spray of acetamiprid 20 % SP @ 0.3 g/L recorded the least disease incidence (7.05 %) and highest seed yield of 5.21 q/ha and while seed treatment with imidacloprid 17.8 SL @ 5 mL/kg + spray of azadirachtin 0.03 % @ 3 mL/kg was least effective with a disease incidence of 11.43 %. The disease incidence in the untreated check was 14.94 % and the lowest seed yield of 3.04 q/ha was recorded (64).

### Cultural practices

The general cultural practices, including timely sowing, proper field sanitation, deep ploughing, summer ploughing, eradicating alternate host plants through weed management and sowing of guard/barrier crops viz. maize, jowar and bajra prevent the pest and disease infestation (65).

Weed hosts are the agents for the spread of disease; hence weeds should be controlled by the application of pre-emergence and post-emergence herbicides to check the weed flora in the sesame ecosystem. Removal of sources of inoculum is an efficient method of reducing mollicute diseases like phyllody spread by oligophagous vectors feeding on infected plants. The removal of infected sesame plants during the cropping season may drastically reduce yield as a result of poor population standing. Hence, as a proactive method, the removal of weeds and other host plants may give an expected level of control. Crop rotation, removal and destruction of infected plants, late sowing, intercropping with pigeon pea (1:1), etc. may act as a proactive management technique to prevent phyllody disease (4). Sesame intercropped with black gram reduced the phyllody incidence. In the intercropped field, phyllody incidence was comparatively less (2.02 % and 6.35 %) as against 6.35 % and 17.96 % in control during the vegetative and flowering stages respectively (10). The reason might be the attraction and sustaining of the population of natural enemies by blackgram and its ultimate action on the leafhopper vectors' population reduction. Concerning the time of sowing, phyllody was highest (33.9 %) in crops sown in November and lowest (0.21 %-0.83 %) in those sown in January, February and September. Earlier studies reported that the lowest disease incidence of 5.66 % in crops sown in February and the highest disease incidence of 22.16 % in August-sown crops (49).

Excessive or inappropriate levels of fertilization to crops can also increase the susceptibility of plants to insect pests and diseases by altering the plant tissue nutrient levels (66). Among the nutritional

factors, a higher dose of nitrogen will provide a congenial substratum for the growth and development of sucking pests throughout the crop growth period (67). A higher population of leaf hoppers, white fly and thrips in cotton was observed at higher doses of nitrogen (69). Concerning other nutrients, phosphorus also decreases the host's susceptibility to various insect-pests. Potassium enhances secondary compound metabolism, reduces carbohydrate accumulation and provides high resistance against insect pests. Secondary macronutrients and micronutrients like calcium, zinc and sulphur were also reported to reduce the insect pest populations (70). Hence, the application of the recommended dose of required fertilizers may help to reduce the vector population and ultimately the phytoplasma infection in sesame.

### Antibiotic treatment

Antibiotic sprays (tetracycline and oxytetracycline) in combination with insecticide and seed treatments were found to be highly effective in the prevention of phyllody incidence (4). Infected sesame plants sprayed with tetracycline- HCl showed partial recovery from the typical disease symptoms after 20-25 days of treatment. However, all symptoms of the disease reappeared on the new branches 45-55 days after tetracycline treatment (29).

### Conclusion

Intensive scanning of the literature showed that researchers from different countries documented the phytoplasma incidence in sesame, different symptoms expressed by the infected plants, vector transmission and genetic diversity of the phytoplasma groups and their subgroups. However, the management technologies for sesame phyllody disease are very minimal. Hence, it could be inferred that the worldwide sesame phytoplasma phyllody incidence may effectively be managed with holistic approaches combining all the package of practices including plant protection measures. Further, most of the released varieties were susceptible to phyllody disease. Phyllody resistant varieties may be developed by crossing the wild species such as *S. alatum*, which is moderately resistant or tolerant to phyllody. Besides, the effector protein responsible for the phyllody development in affected plants may be altered or silenced with biotechnological tools and to be further used in phyllody resistance breeding programme.

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### Authors' contributions

IP, VR, MB worked on conceptualization. IP, PM and HC contributed to formal analysis. Funding acquisition was carried out by IP, HC, BKK. The original draft was written by IP and HC and review and editing were performed by RV, MB, JCH and SG.

## Compliance with ethical standards

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

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