



REVIEW ARTICLE

Advances in sesame phyllody disease: Etiology, vector transmission, epidemiology, diagnosis and integrated management

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Abstract

Sesame (*Sesamum indicum* L.) is an important oilseed crop whose productivity is significantly reduced by phyllody disease. Phytoplasmas present in the phloem tissue of the plant cause sesame witches'-broom disease. The abnormal development of a floral organ into a leaf-like structure (phyllody) and the development into green pigmentation in floral parts (virescence), resulting in sterility and reduced seed production. This disease is common in Africa and Asia and parts of Europe. Infection is mainly through insect vectors, especially the leafhoppers (*Orosius albicinctus*). Phyllody disease-associated phytoplasmas are of diverse ribosomal groups, with the 16SrII group associated with peanut witches'-broom highly prevalent. A fast and accurate diagnosis can be achieved using molecular diagnostics such as polymerase chain reaction (PCR). Phyllody negatively impacts many important agronomic traits of sesame, like plant height, number of capsules per plant and 1000 seed weight. Control of the disease involves some cultural practices (removal of symptomatic plants, use of certified disease-free seeds and change in planting date to avoid peak vector activity); limited chemical control by insecticides aimed only at the vector; and biological practices to improve the efficacy of natural vector antagonists. It seems that it is possible to develop sesame genotypes that are resistant or tolerant to phyllody, making it a sustainable management strategy. Yet, the polygenic nature of phyllody and the complicated nature of the resistance mechanisms have been an impediment. Further studies would be required to understand the ecology of the vectors and phytoplasma-host interaction and to facilitate the development of sesame varieties that have resistance or tolerance to disease. This review summarises current knowledge on the origin, transmission, epidemiology, symptomatology, diagnostics and management of sesame phyllody disease.

Keywords: epidemiology; etiology; management; phyllody; sesame; symptomatology

Introduction

Sesame (*Sesamum indicum* L.) is an important oilseed crop known for its high drought tolerance and adaptability to diverse agro-climatic conditions. Sesame is believed to have originated in Africa, with secondary domestication occurring in the Indian subcontinent (1). Sesame contains a maximum oil content of 63 %, which is significantly higher than that of other major oilseeds like groundnut (45–56 %), sunflower (45 %), rapeseed (40 %) and soybean (20 %) (2). Sesame seeds and sesame oil are enriched with important minerals such as magnesium, phosphorus, calcium, iron and zinc. Sesame seeds are rich in B-complex vitamins and vitamin E and have also been reported to demonstrate powerful antioxidant properties (3, 4). Sesame oil is extracted from sesame seeds which have many health benefits. The oil contains antioxidant components, the lignans

sesamin and sesamol (5, 6). Such oil has antioxidant-component enrichment with sesamol, which enhances oxidative stability in sesame oil (7). Consumption of sesame seeds has been associated with anti-aging, antihypertensive, anticancer, antioxidant and cholesterol-lowering effects (8, 9). Besides human nutrition, sesame is also beneficial for agriculture, processing and gourmet. Leftover cake of sesame seed after extraction of oil has 32 % crude protein and 8–10 % residual oil. Protein feed for livestock, poultry and small ruminants could also be obtained from the seeds (10).

Historical shifts and regional dynamics in global sesame production

Different sesame-producing continents over the years are presented in Fig. 1. Africa has emerged as the leading sesame-producing region in recent years. The data highlights the growing

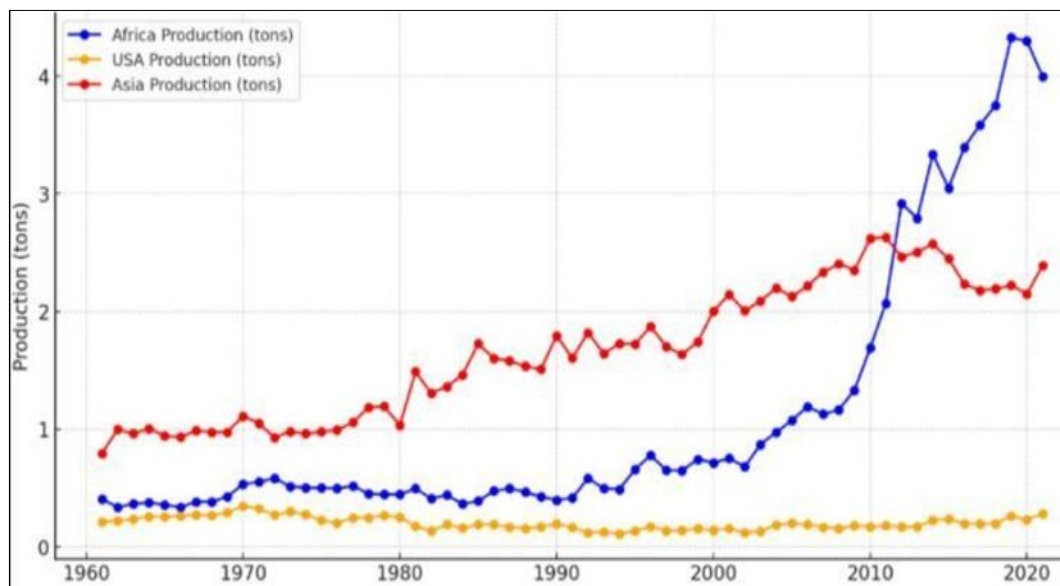


Fig. 1. Trends of sesame production in Africa, USA and Asia, from 1961 to 2021.

(Source: FAOSTAT; 2024 and the authors' visualisation).

importance of African countries in the global sesame market and reveals regional differences in production patterns over the past sixty years. The rise in African sesame production is likely associated with multiple factors, including the expansion of cultivation areas, increasing export demand, the adoption of improved varieties and policy interventions supporting agricultural production and market development (11). Asia was the world's largest sesame producer and its production from 1961 to 2010 remained around 1 to 2 million tonnes. Asia's output peaked at almost 2.5 million tonnes and thereafter plateaued before declining slightly in subsequent years. In contrast, output from Africa was generally low and stable until the early 2000s and subsequently rose significantly. Between the years ranging between 2012 and 2014, Africa surpassed Asia in sesame production. The output rose to a maximum of nearly 4.5 million tonnes in 2020 before a slight drop. On the contrary, the USA had consistently low output levels over the time, with small swings, regularly below 200,000 tonnes. The illustration depicts that Africa is experiencing fast development as the world's leading sesame producer. This means that Africa's sesame production development will change the pattern of sesame growing investment, growth and export demand.

Environmental determinants of sesame growth and the impact of phytoplasma-induced phyllody

The germination and growth of sesame depend on temperature. Germination occurs best at a temperature of about 20 °C, but the performance and yield of crops is believed to be better above 23 °C. Sesame is adapted to a broad temperature range (14.7–47.2 °C), with an optimal temperature of around 35.4 °C for optimal growth and seed development (12). Sesame growth is adversely affected when plants are exposed to temperatures outside their optimum range (13, 14). Adequate water availability through rainfall or irrigation is particularly important during critical growth stages, such as germination, flowering and capsule development, to achieve optimum yield. Therefore, developing varieties with improved water-use efficiency and tolerance to flooding, prolonged drought and waterlogging is essential to minimise adverse effects on plant growth, health and seed productivity (15). Research shows that improving the irrigation process in the vegetative, flowering and fruiting stages can boost sesame yield. The abiotic factors are

salinity, drought, heavy-metal toxicity and nutrient-deficient soils. The biotic include diseases and pests. Over the last decade, the production of sesame and crops has substantially reduced due to biotic concerns, with plant diseases being a major culprit. Phytoplasma-caused disease phyllody is a major constraint on sesame production affecting a large area in Asia and Africa. India is the world's largest producer of sesame; however, its productivity is severely constrained by sesame phyllody disease. The incidence of the disease varies widely among regions, ranging from 10 % to nearly 100 % and can result in up to 80 % reduction in seed yield. Initially, sesame phyllody was believed to be of viral origin (16); however, subsequent studies confirmed that the disease is caused by phytoplasma. The disease was first reported in South Asia and has since emerged as a major threat to sesame production in several sesame-growing regions (17). Symptoms of phyllody disease observed in different sesame cultivars are shown in Fig. 2.

Despite the increasing economic importance of sesame and the expanding geographical distribution of phyllody disease, comprehensive information regarding phytoplasma diversity, epidemiology, symptomatology, vector transmission and integrated disease management remains fragmented. Therefore this review aims to summarise current knowledge on sesame phyllody disease and identify future research directions for sustainable disease management.

Genetic architecture and biotic-abiotic resilience strategies in modern sesame improvement

The main objective of sesame breeding is to develop high-yielding, stable varieties with resistance to major pests and diseases while improving traits associated with market acceptance and end-use quality. Breeding programmes also focus on developing varieties suitable for domestic consumption and export markets through the application of various breeding approaches. In particular, white, large-sized seeds with desirable quality attributes, such as high oil content, favourable fatty acid composition and uniform seed appearance, are preferred in export and confectionary markets. The major breeding objectives are summarised in Fig. 3, whereas the different sesame breeding procedures employed in the sesame improvement programme are illustrated in Fig. 4. Cultivar development must be in synchrony with the local climatic

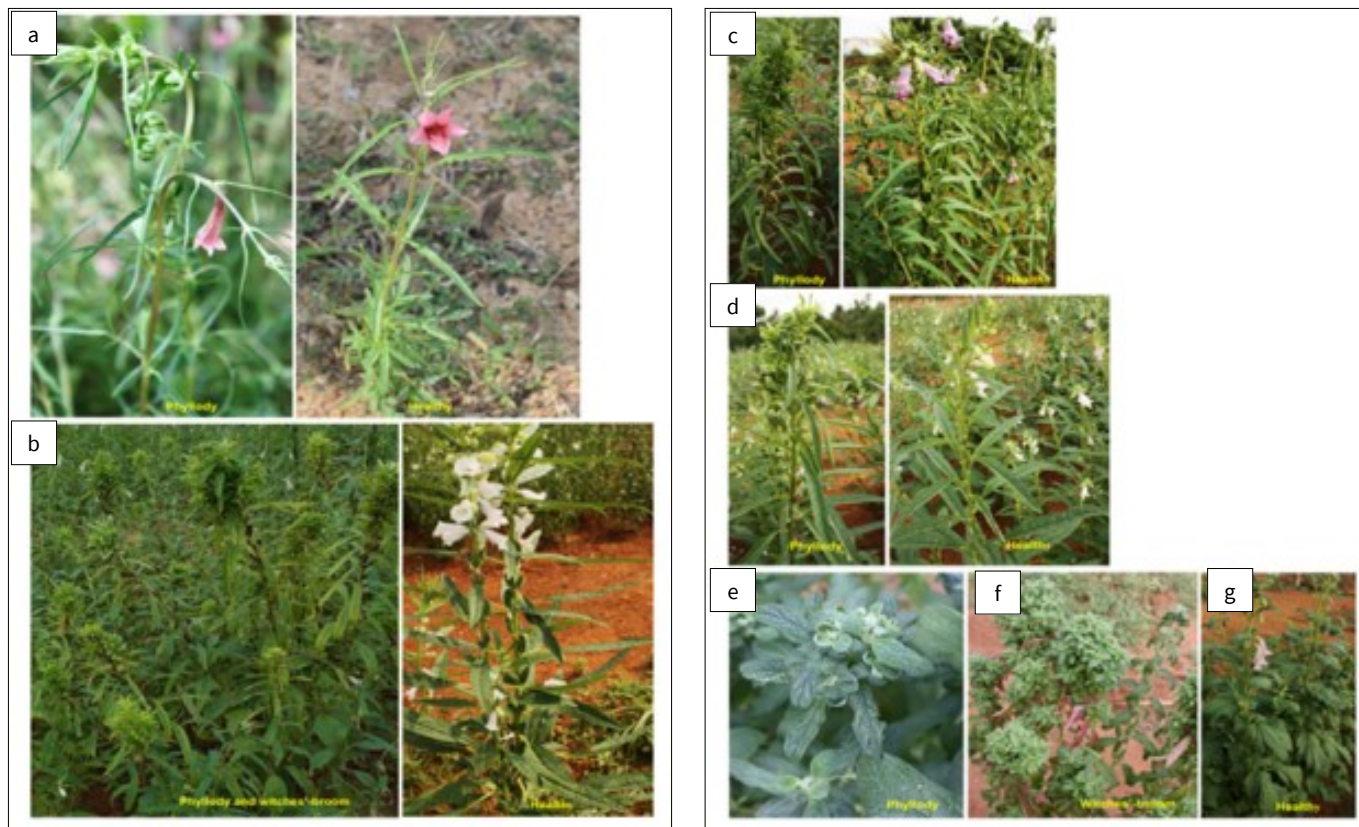


Fig. 2. Phyllody and witches' broom in different species of *Sesamum* depicted with healthy plants. a: *S. alatum*; b: *S. indicum*; c: *S. malabaricum*; d: *S. mulayanum*; e: *S. radiatum*; f: *S. laciniatum*; g: *S. prostratum* (11).

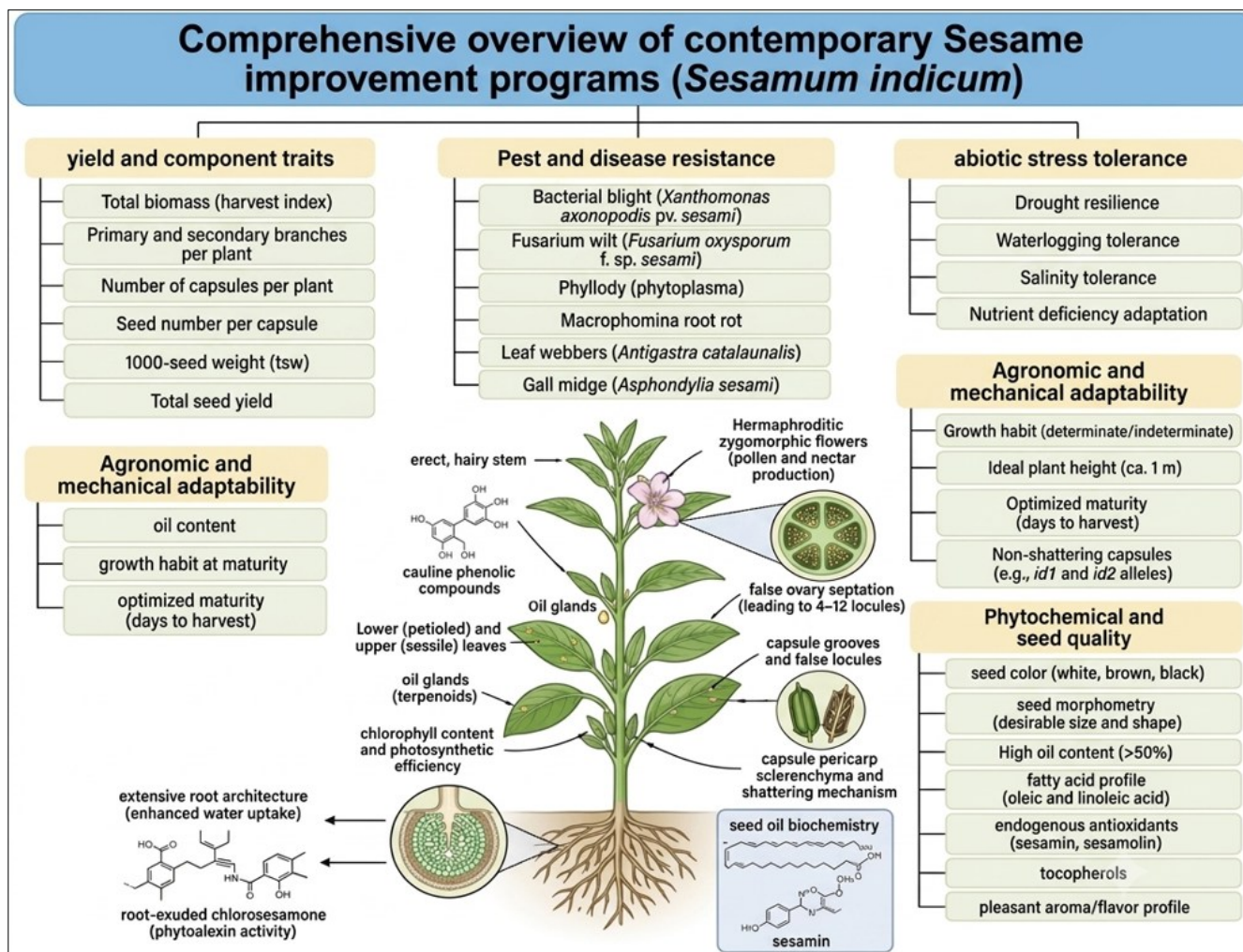


Fig. 3. Comprehensive overview of contemporary improvement in *Sesamum indicum* improvement programs, illustrating breeding objectives, target traits and their physiological and agronomic significance.

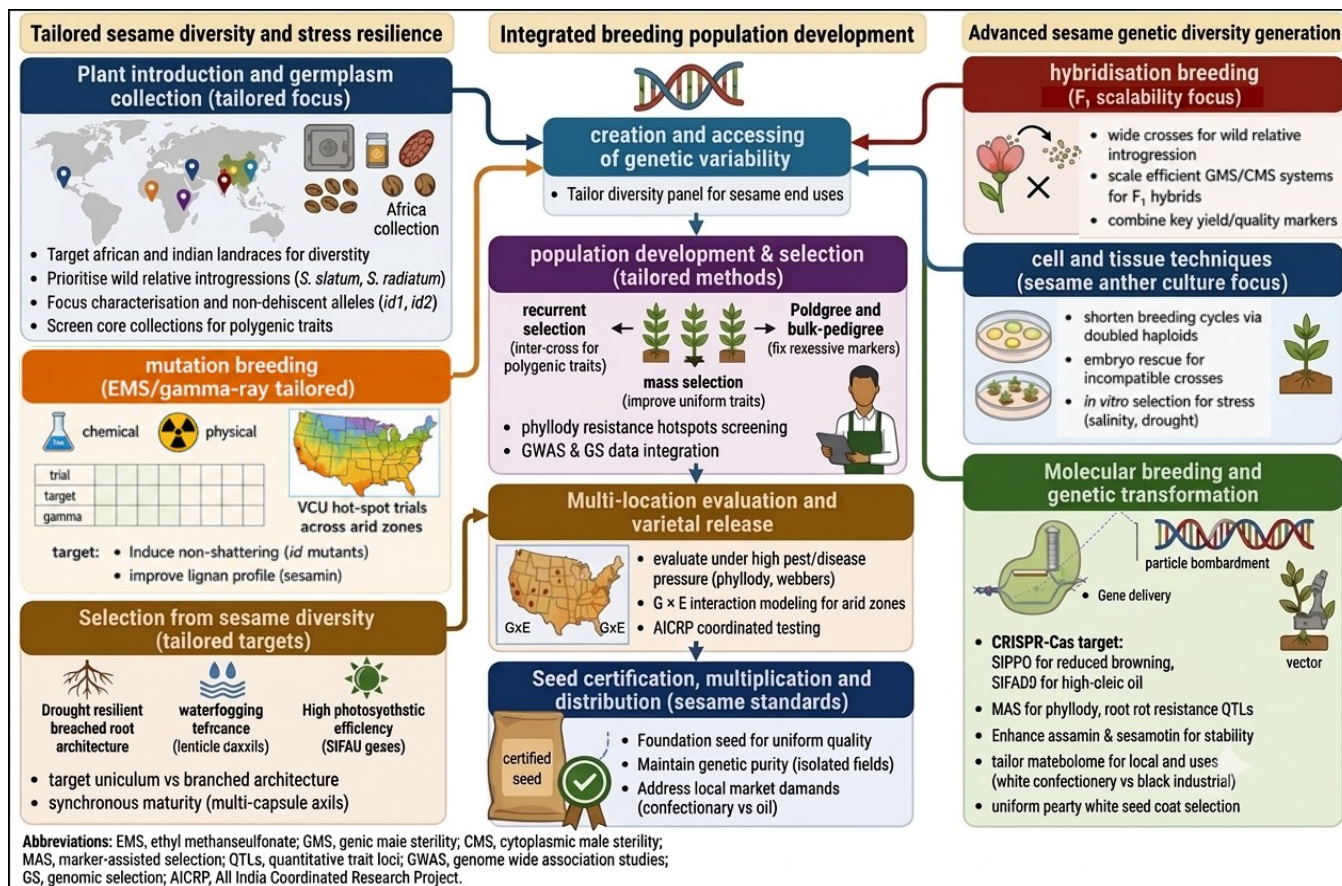


Fig. 4. Conceptual framework for breeding and genetic improvement program for sesame.

conditions. For instance, high-rainfall regions necessitate a lack of susceptibility to bacterial blight. Rainfed areas demand early maturation and irrigated regions require a lack of susceptibility to phyllody. Many existing cultivars and breeding lines are still poorly adapted to the local practices of production and local environments. A key objective of sesame breeding is to develop high-performing, adaptable genotypes with early to medium maturity and enhanced tolerance to biotic and abiotic stresses, enabling stable production across diverse and changing agro-ecological conditions. Enhancement of yield potential depends on key yield-contributing traits such as capsule number per plant, seeds per capsule and thousand-seed weight. Genotypes with capsules having eight locules improve seed yield. Improvement of plant architectural traits, including plant height, branching habit, capsule distribution, stem strength and maturity duration, is essential for enhancing the harvest index. An ideal plant architecture includes moderate plant height (~1 m) with clustered capsules positioned 15–20 cm above ground level. Globally, seed yield is about 340 kg/ha under low-input management. Yields over 2250 kg/ha have however been reported from intensive agricultural management systems. The genotypes which are made for certain ideotypes and with broad adaptability have greater responsiveness to multiple agronomic inputs and weather changes.

Production of sesame is greatly affected by biotic stresses. In rainy places, the crop is prone to infection by several pathogens such as bacterial blight, fusarium wilt and charcoal rot. The insect pests of sesame are (i) leaf webbers or rollers, (ii) capsule borers or also called as *Antigastra catalaunalis* (iii) sphinx moths or also called as *Acherontia styx* (iv) aphid (*Aphis gossypii*) and (v) gall midge (*Asphondylia sesami*). As sesame is usually cultivated in marginal areas by small and marginal farmers, abiotic stresses are major limiting factors for its cultivation. Drought resistance and improved

water-use efficiency mechanisms may be enhanced but output still remains constrained due to susceptibility to salinity, waterlogging and chilling. Hence the main thrust is breeding for abiotic stress resistance. When the capsules burst at maturity due to lack of moisture stress around capsule pericarp it is an important problem which has a high impact on yield. Most of the presently cultivated varieties are the shattering types. Capsule shattering can result in yield losses of up to 60–70 %, particularly under dry harvesting conditions (18). Efforts are ongoing to minimise these losses by developing semi-indehiscent high-yielding varieties for mechanical harvesting. Higher yields of mature seeds and seed oil content are required to increase oil yield from sesame. Under ideal circumstances, though, the oil content of seeds should be over 50 %. White-seeded types usually have higher oil contents than dark-seeded types. The composition of sesame oil is nutritionally ideally rich in the unsaturated fatty acid, oleic acid and linoleic acid. Sesame seeds contain natural antioxidants (sesamol, sesaminol, tocopherols, etc.) with the potential to enhance oil quality and export potential. For confectionary and processing purposes, breeding lines should exhibit desirable seed characteristics such as an appropriate seed colour, shape and size. White-seeded cultivars are especially useful as they are the most sought after in the world market due to its high oil content. The extra quality factors, which are crucial for use in confectionery, halwa, bakery and premium sesame oil are seed coat texture, oil aroma and taste and dehulling efficiency.

Nutritional profiles, industrial applications and global market dynamics of sesame

Sesame (*S. indicum*), is an important foodstuff possessing about 20 % protein and about 50 % edible oil. The oil has a high unsaturated fatty acid content, with oleic acid (47 %) and linoleic acid (39 %) being the predominant constituents. Sesame oil has a phenolic antioxidant known as sesamol (19, 20). This antioxidant

makes the oil strong and reduces oxidative rancidity. In the last two decades, demand for sesame has increased in various parts of the world due to its oil quality, high protein, antioxidant levels and ability to survive adverse weather conditions (21, 22). The crop belongs to the family Pedaliaceae, whose basic chromosome numbers are $n = 8$ or 13 . Several species are known to be tetraploids or octaploids (23). The annual sesame plant has a very unpredictable development and an estimated 350 Mb genome size. Sesame seeds are referred to by different vernacular names across India, such as til (Hindi and Gujarati), till (Punjabi), nuvvulu (Telugu), ellu (Tamil) and tila (Odiya). It is one of the first crops ever grown and is a staple food of poor farmers in Africa and Asia. It is believed that the place of origin for this species being Africa, though the Indian subcontinent may also be the place of early domestication. Sesame is the 10th most valuable of the thirteen oilseed crops that contribute 90 % of world edible oil production (24). The top sesame producing countries include Tanzania, Sudan, Myanmar, India and China. India produces sesame on a large scale across several regions being main producers including Rajasthan, Madhya Pradesh, Uttar Pradesh, Andhra Pradesh, Gujarat, Maharashtra, Tamil Nadu, Odisha and Bihar.

The use of sesame oil in the world is projected to be more than 100 million metric tonnes by 2030 (25). This crop improves soil structure and drought resistance due to its well-developed root system. Sesame is a fairly resistant crop but a low-yielding crop because of capsule cracking. The white seeded sesame type has approximately 25.18 % protein with reasonable quantities of the essential amino acids, tryptophan and methionine. The consumption of sesame increases the level of tocopherol in plasma and enhances the effectiveness of vitamin E. Sesame roots contain a chemical called chlorosessamone that researchers are investigating for use in generating biodiesel. The semidrying properties of

chlorosessamone are useful in paint formulations (26). When the oil is extracted, the remaining meal has about 30–35 % protein. This makes it a good feed for cattle and poultry. Natural antioxidants including sesamin, sesamol, γ -tocopherol and sesamol prevent rancidity of the oil. Owing to its diverse nutritional, economic and industrial applications (Fig. 5), sesame is often referred to as the ‘queen of oilseeds’

Taxonomic classification of family Pedaliaceae and karyotypic variations in sesame

Sesamum indicum is a plant species belonging to the family Pedaliaceae. It is a diploid organism and is composed of 26 chromosomes. Its vulnerabilities during reproduction make seeds sessile. The Pedaliaceae plant family encompasses 16 distinct genera, featuring *Pedaliaceae*, *Ceratotheca* and *Sesamum* plant. *Sesamum* contains substantial chromosomal diversity as evidenced by documentation of bare chromosome counts of 13 and 16. The cultivated species, *S. indicum* plants have a base chromosome number of 13 (27, 28). Recent cytogenetic analyses have classified sesame species into three chromosomal groupings (28, 29) (Table 1); Group I: Diploids with $2n = 2x = 26$, encompassing *S. indicum*, *Sesamum alatum* Thonn. and *Sesamum capense* Burm.f.; Group II: Diploids with $2n = 2x = 32$, including *Sesamum latifolium* J.B.Gillett, *Sesamum angolense* Welw., *Sesamum calycinum* Welw. and *Sesamum angustifolium* (Oliv.) Engl. as shown in Fig. 6A; Group III: Tetraploids with $2n = 2x = 64$, including *Sesamum radiatum* Thonn. ex Homem., *Sesamum occidentale* Heer & Regel, as shown in Fig. 6B. The genus *Sesamum* comprises several species distributed across Africa and Asia, with Africa representing the primary centre of diversity, while a few isolated occurrences have also been reported from Brazil and the Greek islands (23). Subsequently, a revision by IPGRI and NBPGR (2004) acknowledged just 17 genuine species, mostly of African origin (30).

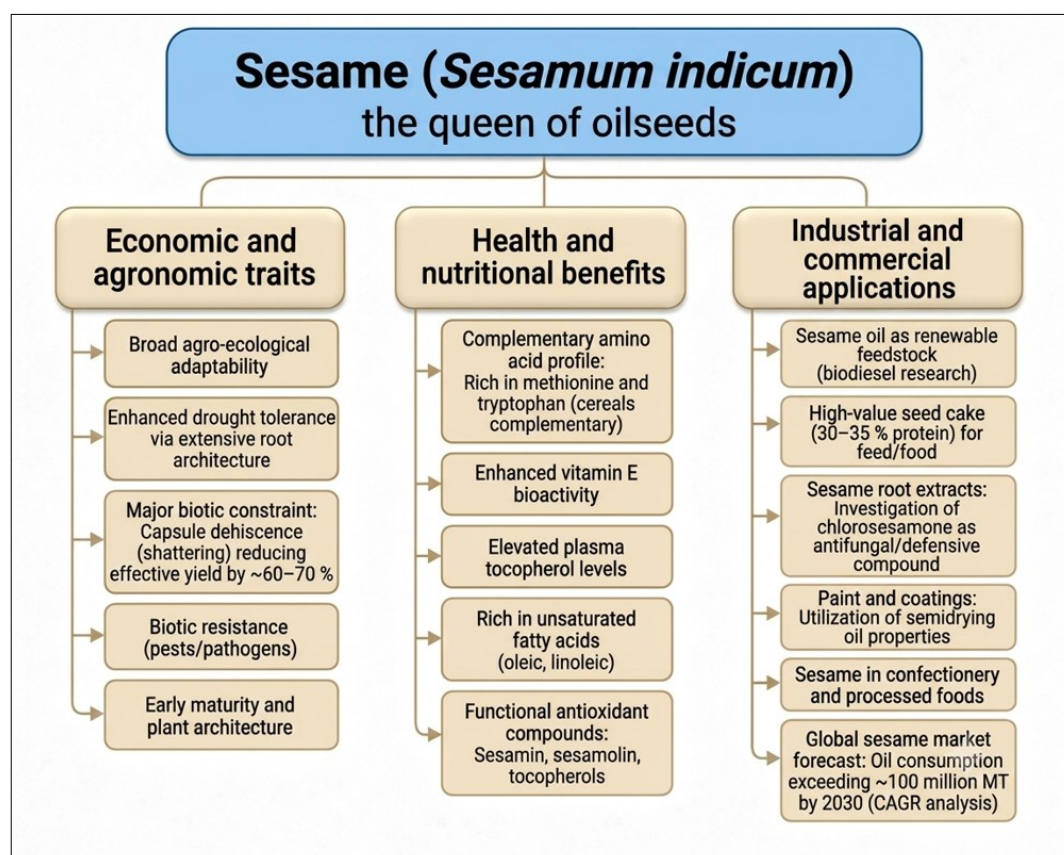


Fig. 5. Multidimensional value chain analysis of sesame.

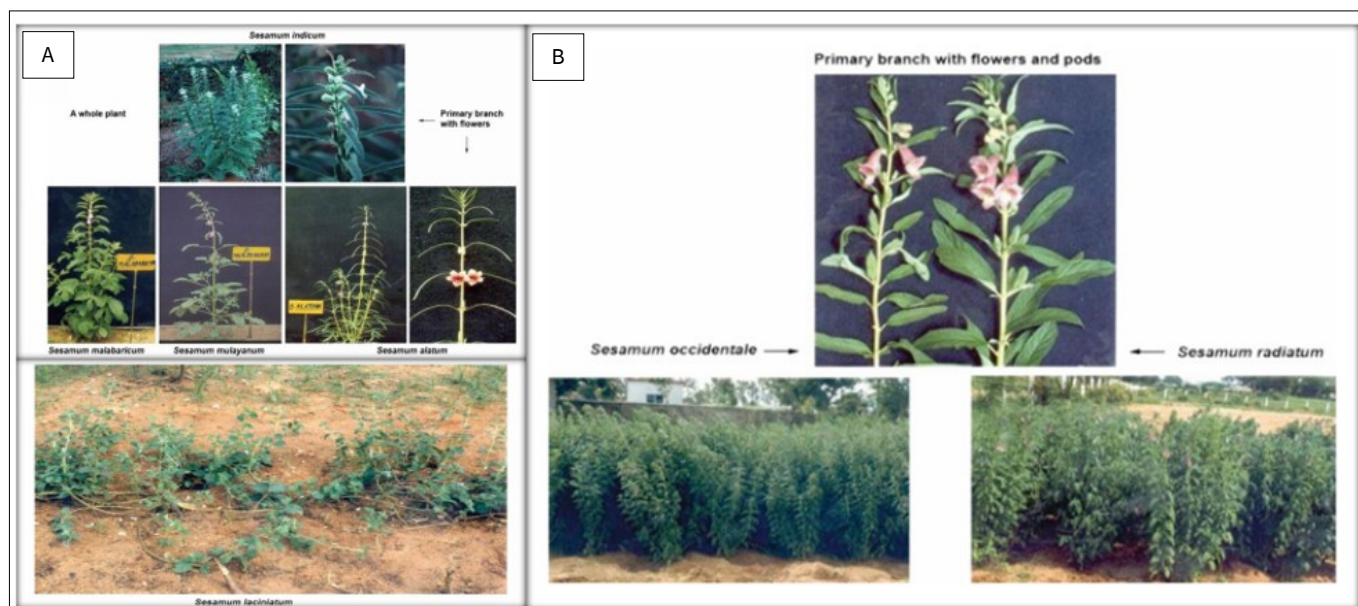


Fig. 6. (A) Diploid sesame species; (B) Tetraploid sesame species.

Table 1. Classification of Sesamum species based on chromosome number

Group	Chromosome number	Sesamum species
I	2n = 26	<i>S. indicum</i> , <i>S. latum</i> , <i>S. capense</i> , <i>S. malabaricum</i> , <i>S. mulyanum</i> , <i>S. schenckii</i> , <i>S. africanum</i>
II	2n = 32	<i>S. prostratum</i> , <i>S. laciniatum</i> , <i>S. angolense</i> , <i>S. angustifolium</i>
III	2n = 64	<i>S. radiatum</i> , <i>S. occidentale</i> , <i>S. schinzianum</i>

Floral ontogeny, organography and phenological dynamics of anthesis

Sesame is an erect, annual herb exhibiting determinate or indeterminate growth habits depending on genotype, typically reaching heights of 50–100 cm. The stem has hairs and ridges sparsely. The shape of the leaf changes on the stem. The leaves that are lower down have sessile leaves while those that are higher have petiolate leaves. The length of the leaves varies from 4–14 cm which is entire and less frequently lobed. The leaves at the base are broad-lanceolate and have a width of 5 cm. Above these, the leaves are smaller and have a width of 1 cm. Leaf arrangement in sesame is opposite at lower and alternate above and has oil glands on the dorsal side as shown in Fig. 7A. Flowers arise from leaf axils, not the base of the plant. These are structures that appear like tubes, measuring 3 to 5 cm long, zygomorphic with 4 lobes. The most

popular flower colour is white but pink, purple and bi-coloured flowers are also available as shown in Fig. 7B. Each flower as shown in Fig. 7C is hermaphroditic and typically occurs singly or in clusters. A total of four didynamous stamens are present that consist of two long and two short stamens. The stamens have dorsifixed and epipetalous filaments whose anthers dehisce lengthwise. The style is elongated, the stigma bifid, with superior (hypogynous), multi-carpellate gynoecium. The ovary is encircled by a nectary disk that attracts pollinators by the production of nectar. The calyx has five joined sepals and the corolla has lobes with one of the petals usually being a landing site for pollinators. Sesame bears a dehiscent, hairy capsule with a rectangular transverse section, several longitudinal grooves and a small beak at the end as shown in Fig. 7B. Capsule length varies from 2 to 8 cm and diameter from 0.5 to 2 cm, with the number of locules ranging from four to twelve depending on the genotype Fig. 7C (31). Dehiscence occurs longitudinally along the septa or through apical pores depending upon cultivar characteristics. At physiological maturity, sesame seeds exhibit variation in seed coat colour depending on genotype, ranging from white and biscuit to black as shown in Fig. 7D. Stigma receptivity is specific for genotype, often lasting up to 24 hr after anthesis (32). Other studies suggest that viability decreases within 14 hr of anthesis (33). Receptivity usually occurs 2 hr after the flower has opened (34). Pollen is viable for about 24 hr after dehiscence at optimal temperatures of 24–27 °C (33).

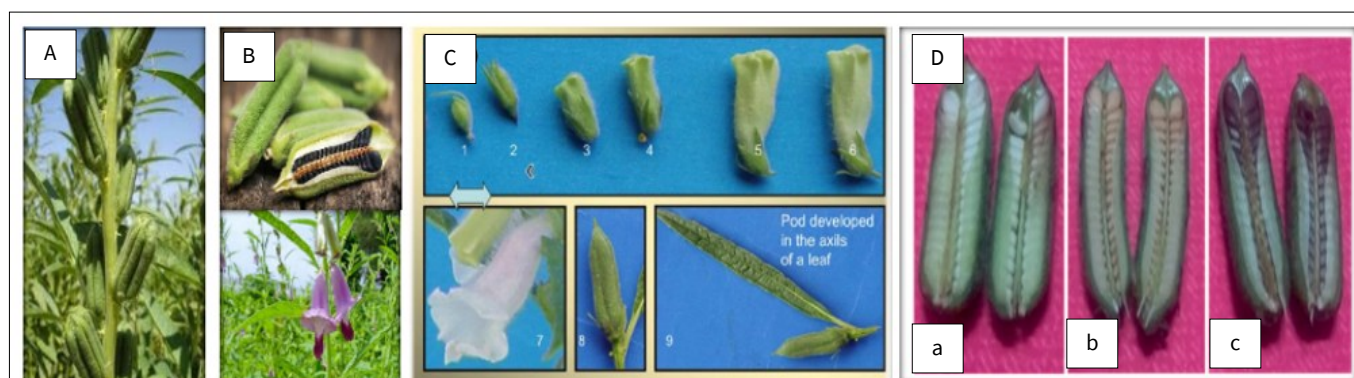


Fig. 7. Morphological characteristics and developmental stages of sesame. A: Plant at the capsule stage; B: capsule and purple bell-shaped flower; C: flower developmental stages; D: seed colour at physiological maturity- a: white; b: biscuit; c: black.

Comparative pathosystem analysis of *Candidatus Phytoplasma* strains across cultivated and wild genus *Sesamum*

Phyllody is a severe and destructive disease that affects sesame, a major oilseed crop that is generally cultivated in the tropical and subtropical regions of the world. Cultivated sesame and wild species such as *S. alatum*, *S. indicum*, *S. occidentale* and *S. radiatum* have recorded severe infections of this disease (35, 36). In India, there are reports of virescence signs from a number of *Sesamum* species having varied susceptibility of which *S. alatum* was noted as the least susceptible. The strain of *S. indicum* has been identified as *Candidatus Phytoplasma asteris*. Strains associated with other species, such as *S. radiatum*, *Sesamum malabaricum* Burm., *Sesamum mulayanum* N.C.Nair, *Sesamum prostratum* Retz., *Sesamum laciniatum* J.G.Klein ex Willd., are *Candidatus Phytoplasma australasiae* (37). Phyllody is characterised by the transformation of floral organs into leaf-like structures due to *phytoplasma*-induced developmental reprogramming. Floral malformation is a moderate type of flower defect that affects reproductive growth and yield potential. In states like Bihar, the disease is endemic. The severity of the disease varies according to agroclimatic conditions, mode of agricultural practices and vector population. It is very important to understand the time of sesame cultivation and its relation with the climatic factors so that effective disease control techniques may be developed, as the disease is transmitted by leafhoppers, especially *O. albicinctus*. Genetic studies indicate that a dominant gene is present in wild species while a recessive gene is present in cultivated varieties for phyllody resistance (38). *Phytoplasma* infection reduces relative leaf water content, chlorophyll concentration and photosynthetic capacity, resulting in stunted plant growth (39, 40). Healthy leaves are the primary sites of photosynthesis; however, leaves produced on phyllody-induced witches' broom shoots exhibit markedly reduced photosynthetic efficiency (39, 40). In addition, floral malformation, sterility, poor seed set and the formation of seedless capsules collectively contribute to substantial yield losses. Damage is associated with hormonal imbalances and *phytoplasma* effector activity (41). Plants affected by phyllody disease have reduced values of yield-contributing traits. Studies show that when 25 % of the reproductive development of a plant is compromised, yields will drop by 39.73 % (42). Infected plants show a loss of about 18 % in oil content (43, 44). The disease has also an unfavorable effect on germination percentage and test weight (45).

Etiological classification, vector dynamics and regional phylogeography of sesame phytoplasmas

Sesame phyllody is caused by phytoplasmas, which are wall-less, phloem-limited prokaryotes belonging to the class Mollicutes. The disease is associated with phytoplasmas belonging to the 16SrI, 16SrII, 16SrVI and 16SrIX ribosomal groups. *Phytoplasma* infection is the primary cause of the disease and is transmitted by leafhopper vectors. *Orosius albicinctus* has been identified as a carrier in Iran (46); however, recent research in India recognises *Hishimonus phycitis* as another key vector (47, 48). Phytoplasmas are transmitted through infected vegetative propagules, parasitic plant bridges such as *Cuscuta* spp. and insect vectors, primarily leafhoppers. The phytoplasmas are obligate parasites which reside in the phloem tissues of plants and are disseminated to other plants through the insect vectors; in general, leafhoppers which acquire them from a diseased plant and re-inoculate the healthy plant from their saliva.

After feeding on infected plants, the *Phytoplasma* is received by the vector, followed by its systemic movement and multiplication within the insect's salivary glands in the transmission cycle. Phytoplasmas are transmitted to healthy plants during subsequent feeding (49). Characterisation through nested polymerase chain reaction (PCR), sequencing, restriction fragment length polymorphism (RFLP), phylogenetic analysis and multilocus sequence analysis (MLSA) using the 16S rRNA gene alongside additional marker genes has improved the classification associated with mild leaf yellowing disease (50, 51). The sesame samples exhibiting symptoms were collected from nine states of India and studied. It was reported that the infections were mainly due to two *phytoplasma* groups, namely 16SrI and 16SrII (52). A majority of 16SrI-B was found in North India. In contrast, only 16SrII was reported in South India.

The main *Phytoplasma* group associated with sesame phyllody belongs to the peanut witches' broom (16SrII) group. *Catharanthus roseus* (L.) G.Don, a member of the family Apocynaceae, is a perennial herbaceous vegetation. Because of its exceptional susceptibility and ability to maintain the phytoplasma at high titers, it serves as a model host for phytoplasma studies. This property makes it an excellent tool to study the host-pathogen interactions (53). Alongside this, it is also useful for the long-term storage of phytoplasma isolates. Dodder-mediated, graft and sap transmission studies have been widely used to investigate the transmission biology of sesame phyllody phytoplasma and confirm its infectious nature. Dodder (*Cuscuta campestris*) serves as an effective bridge between infected and healthy plants, facilitating phytoplasma transfer and demonstrating its ability to spread between different host species (53, 54). Dodder-mediated transmission is illustrated in Fig. 8A, whereas graft transmission is shown in Fig. 8B. Similarly, successful graft transmission has confirmed the systemic movement of phytoplasmas within infected plant tissues. Sap transmission studies further support the infectivity of the pathogen, although transmission efficiency may vary. Collectively, these approaches have contributed significantly to understanding the epidemiology, host-pathogen interactions and dissemination pathways of sesame phyllody, thereby aiding the development of effective disease management strategies (53–56).

Macro-climatic determinants, seasonal correlations and predictive modelling of disease incidence

The epidemiology of phyllody disease in sesame is influenced by complex interactions between vectors, climate, crop stage and availability of alternative host species. A warm and damp environment aids in multiplication of *Phytoplasma* as well as insect vectors which causes an increase in the disease. The incidence of disease during the kharif season had a positive relationship with maximum temperature and diurnal temperature range while it exhibits a negative relationship with wind speed, total rainfall and number of wet days. Disease prediction models were found to be quite reliable, with summer accuracy reaching 97 % and kharif accuracy of 95 % (57). Phyllody severely reduces plant growth and yield response, lowering the seed oil content and adversely affecting the oil quality. Crop sown in mid-July experienced peak disease incidence, whereas, in the crop sown in late August, reduced incidence was recorded (58–60). In Saurashtra, sesame sown from late May to mid-June was found to be more susceptible than sesame sown from late June to early July (61).

During summer, higher numbers of the leafhopper vector, *H. phycitis*, coincided with rise in maximum and minimum temperatures, increased relative humidity in the morning and decreased wind speed and sunshine hour, which favourably enhanced transmission of *Phytoplasma* (57). Leafhoppers are the major insect vectors of phytoplasmas, which cause phyllody. As planting schedules and weather conditions determine the vector population, their population dynamics depend on these. For example, leafhoppers were the least found in the crops of sesame sowed in February, reached their peak in their numbers in the crops sowed in the beginning of August and then there was a drop (57). Vector abundance was positively influenced by temperature and relative humidity (62). The genetic makeup of sesame species dictates their susceptibility to phyllody (63). The seven *Sesamum* species studied were all susceptible to the disease to varying degrees. *Sesamum alatum* had the lowest frequency (0–6 %) within this category, with *S. laciniatum* (11–17 %) and *S. prostratum* (16–27 %) showing the next lowest frequency (7–11 %). Elevated occurrences (44–68 %) were documented in *S. indicum*, *S. malabaricum*, *S. mulayanum* and *S. radiatum* (64). Crop production systems are crucial for phyllody epidemiology because of regional agricultural practices in India, especially Bihar. As rice is grown in the kharif period, conditions become favourable for leafhoppers; and this indirectly increases the incidence of phyllody in nearby sesame fields. The beginning of the disease is usually associated with the crop stage particularly with its blooming. Mid kharif season with ideal temperature and humidity favours the activities of the vectors and dissemination of disease but the rainfall hinders the vector activities. The disease phyllody incidence was highest during the second half of December with intermediate incidence between October to March (65).

Macroscopic symptom expression, phenotypic plasticity and genetic diagnostics of sesame phyllody

Infected sesame plants show symptoms depending on the development stage the plants become infected. The early stage of infection results in chlorosis, stunting and a reduction in leaf size but infections at later development stages show up as virescence, floral proliferation, phyllody and pod cracking or deformity. Sometimes plants that get infected late can still produce small shrivelled capsules (61, 66). Initially the symptom is found as vein clearing and is clearly visible during the flowering stage. Floral organs get converted into green, leaf-like structures and develop abnormally leading to floral sterility (67).

Phyllody symptoms illustrated in Fig. 8C, demonstrate their appearance and intensity depending on several parameters. These parameters include phytoplasma strain, host genotype, plant age at the time of infection, disease development stage and the environmental condition in which disease occurs (68). Mycoplasma-like organisms called phytoplasmas are responsible for the disease and they are mainly transmitted through leafhoppers (69). Plants that contract infections display stunted growth and are unable to produce viable reproductive parts. These factors lead to severe downturn in harvests as much as 33.9 % in extreme cases (70). Floral abnormalities are a typical symptom in which a floral organ of reproduction (petals, stamens and pistils) are transformed into green leaf like structures (phyllody). Infected plants are generally stunted and exhibit poor vigour. The leaves develop chlorosis, which is often associated with nutrient deficiency or impaired photosynthesis. Proliferation of abnormal axillary shoots results in a dense, bushy appearance. Floral sterility prevents normal capsule development, leading to a substantial reduction in seed production. Although the initial diagnosis of phyllody is based on visual symptoms, accurate identification requires molecular confirmation.

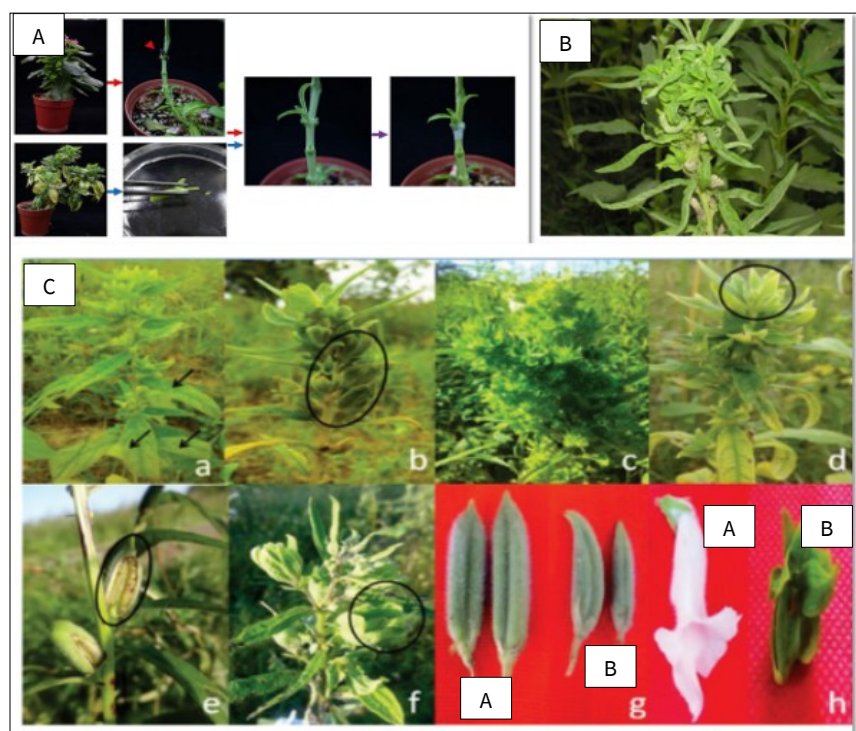


Fig. 8. Methods used for phytoplasma transmission and symptoms of sesame phyllody. A: Diagram of the grafting technique showing a diseased scion from a phytoplasma-infected plant cut into a V-shape and inserted into a slanting cut made on a healthy periwinkle stock plant. The red arrowhead indicates the grafting site (31); B: Symptoms of sesame phyllody following phytoplasma inoculation using dodder as a bridge and periwinkle as the donor plant (12); C: Symptoms of sesame phyllody- a: yellowing of leaves; b: flower virescence; c: flower proliferation; d: phyllody; e: pod cracking; f: shoot-like structure of the ovary; g: healthy and infected pods; h: healthy and infected flowers (35).

Molecular and genetic diagnostic methods are essential for accurate detection and characterisation of sesame phyllody phytoplasmas. In addition to conventional PCR, nested PCR is widely used as it is highly sensitive in detecting low titres of phytoplasma in symptomatic and asymptomatic tissues (71). Quantitative real-time PCR (qPCR) provides early detection and quantitation of pathogen load, while loop-mediated isothermal amplification (LAMP) allows for rapid, cost-effective and field-deployable diagnosis (72, 73). The 16S rRNA gene phylogenetic analysis remains the gold standard for phytoplasma identification (50). However, multilocus sequence analysis (MLSA) based on additional markers such as *secY*, *tuf*, *rp* and *groEL*, offers higher resolution to distinguish closely related strains and improve taxonomic resolution (74).

Methodological advancements in *Phytoplasma* identification from cytological staining to multi-locus sequence typing (MLST)

Phyllody disease is assessed using the disease scoring scale (0–6) (Table 2) (65). Percentage disease incidence is the quotient of the number of diseased plants to the total number of plants, multiplied by one hundred (75). Prior to the 1980s, the primary means of detecting phytoplasma-associated diseases relied on cytological staining techniques such as Diene's and DAPI staining (76–78) and transmission electron microscopy (79). In India, serological techniques (enzyme-linked immunosorbent assay, ELISA) have been used very sparingly, rarely if ever, for diagnosing infections in crops like brinjal and sugarcane (80, 81). In the early 2000s, extensive use of PCR revolutionised diagnosis of phytoplasmas. At the present time, the most reliable phytoplasma detection technique in plants and insects is the PCR amplification of the 16S rRNA gene, especially nested PCR with RFLP analysis (82). Due to the great conservation of the 16S rRNA gene, it has become essential for the classification of phytoplasmas into the group '*Candidatus Phytoplasma*' ribosomal groups and subgroups. However, due to the conservative nature of the 16S rRNA gene, it cannot distinguish between close phytoplasma strains. Certain subgroups may contain strains that exhibit different biological features. The MLSA has proven to be a better phylogenetic option and offers superior resolution to differentiate between the strains (83, 84). Researchers in India have increasingly used moderately conserved housekeeping and effector genes for better classification. For example, *secA*, *secY*, *tuf*, *groEL*, *leuS*, *gyrA*, *imp*, *dnaB*, *dnaK*, *gyrB*, *SAP11* and *rp* have been used for the molecular identification and differentiation of phytoplasma isolates. This is especially the case when 16S rRNA sequences are inadequate (85–89).

Table 2. Scoring of phyllody disease using the disease scoring scale for genotype

Disease score	Plant infection (%)	Resistance categories
0	0	Highly resistant
1	0.10–10	Resistant
2	10.10–20	Moderately resistant
3	20.10–30	Tolerant
4	30.10–40	Moderately susceptible
5	40.10–50	Susceptible
6	>50	Highly susceptible

Spatiotemporal fluctuations and regional micro-climatic correlations of vector abundance

The population dynamics of leafhoppers, namely *O. albicinctus*, a recognised vector of phyllody disease in sesame (*S. indicum*), are profoundly affected by meteorological factors, planting schedules

and seasonal fluctuations. Numerous field investigations undertaken in various agro-climatic zones of India have clarified the correlations between environmental conditions and leafhopper prevalence throughout the kharif and summer seasons. Sesame crops planted on June 5 during the kharif seasons from 2002 to 2004 had the greatest prevalence of phyllody disease (28.6 %) and an average leafhopper density of about 15 insects per plant (80). Conversely, postponed planting on July 15 and 25 led to markedly reduced disease incidence (~15 %) and vector populations. The research observed that leafhopper density exerted a non-significant influence on total disease incidence, underscoring the possible impact of other epidemiological parameters (90). Gwalior (kharif 2019) that *O. albicinctus* populations demonstrated positive correlations with evening relative humidity and rainfall, while exhibiting negative associations with evaporation rates, implying that humid conditions are conducive to vector proliferation (91). Leafhopper numbers in Coimbatore peaked around standard meteorological weeks (SMW) 37–40, based on their research conducted in kharif and rabi 2020 (92). The abundance exhibited a substantial association with relative humidity, although correlations with temperature and evaporation were inconsistent, perhaps influenced by pest-specific reactions to environmental variations.

Role of sowing date and agro-environmental conditions in sesame phyllody epidemiology

A study conducted in Tirupati during kharif 2018 revealed that early planting on June 21 resulted in an increase in leafhopper density and phyllody symptoms. Postponed sowing till July decreased both parameters significantly showing the epidemiological importance of sowing time. The Bundelkhand region in Madhya Pradesh was used for an incidence study which occurred seasonally. The sesame crop was planted on July 20 and it reported maximum incidence of phyllody (21.6 %). It was also observed that the density of leafhoppers was maximum (about 0.84 leafhoppers per leaf). The range which was sown on August 10 reported minimum incidence (6.64 %) disease and also lesser count of insects (about 0.52/ leaf). The delay of planting results in higher yield, thus, crop production scheduling plays an important factor in pest management (93).

Phenological sowing window optimisation and relative yield forecasting under biotic stress

In all studies, early sowing periods (late May to early July) consistently led to increased vector pressure and more phyllody incidence. Leafhoppers are usually active during the mid-kharif season. Environmental influences on the leafhopper vectors transmitting phyllody phytoplasma in sesame are discussed in this review. Moderate to heavy rains, evening relative humidity and temperature regulation were found to increase vector activation, proficiency levels and ultimately the chance of disease development. On the other hand, high evaporation, more sunlight and delayed planting are all negative environmental factors reducing vector survival and activity. The high constituent interaction of these abiotic parameters influences the phyllody disease epidemiology necessitating integrated pest control programming to synchronise sowing time with the condition unfavourable for vector multiplication for successful combat against disease and to promote healthy crop growth. The forecast model (Fig. 9) shows impact of sowing date on population dynamics of leafhopper, the incidence of phyllody disease and relative yield in sesame. Research from multiple field studies shows that early planting between June 5 and June 21 is consistently associated with

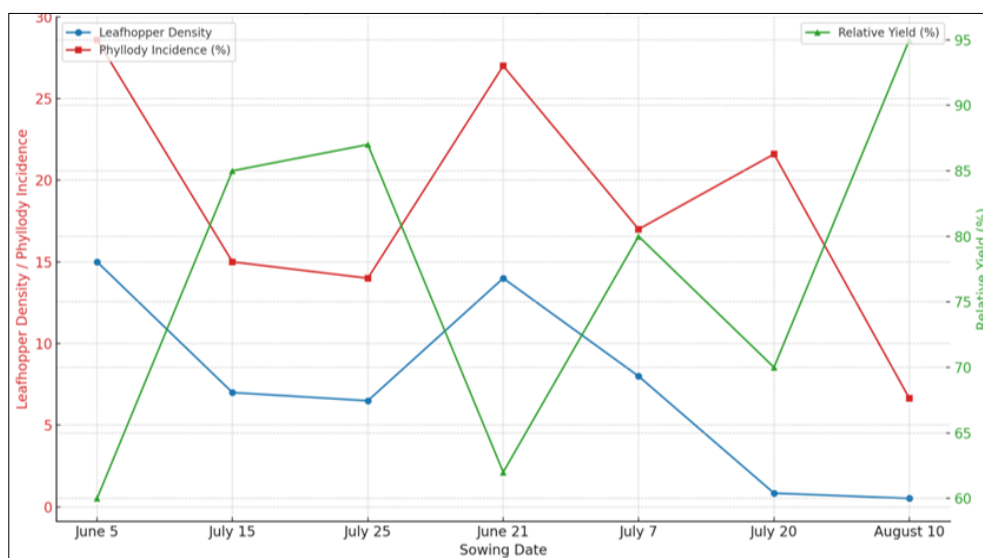


Fig. 9. Predictive model of sowing dates on leafhopper population dynamics, phyllody disease incidence and relative yield in sesame cultivation.

much higher leafhopper densities (up to 15/plant) and phyllody incidence (28.6 %). The presence of pests and diseases applies pressure on yield potential. This pressure could potentially reduce relative yield to 65–70 % as compared to optimum planting dates. On the other hand, late seeding, which is estimated around August 10, has led to a drop in the vector with 0.52 leafhoppers per leaf and 6.6 % disease incidence, resulting in a relative yield increase of 90 %. Climatic parameters impact these patterns in vector and disease transmission. Higher maximum and minimum temperatures with high evening relative humidity promote vector activity and disease transmission while increased wind speed, duration of sunshine and frequency of rainfall suppress it. The model suggests that if the planting windows can be regulated preferably between mid-July and early August then sesame-yields can be improved under biotic stress and changing agro-climatic condition.

Several studies have shown that early sowing periods, particularly during June and July, are associated with increased leafhopper activity and a higher incidence of sesame phyllody. Environmental factors such as moderate rainfall, elevated evening relative humidity and favourable temperatures enhance vector multiplication and phytoplasma transmission, whereas increased sunshine duration, wind speed and delayed sowing tend to

suppress vector activity and disease development. The interaction among these abiotic factors strongly influences sesame phyllody epidemiology, highlighting the importance of integrating sowing time with periods that are unfavourable for vector proliferation. A forecast model (Fig. 9) illustrates the influence of sowing date on leafhopper population dynamics, phyllody incidence and sesame productivity. Evidence from field studies indicates that July sowings are associated with higher disease pressure than later sowings, while delayed planting can reduce vector abundance and disease incidence, thereby improving crop performance. Therefore, adjusting the sowing window to mid-July or early August may help minimise disease severity and enhance sesame productivity under changing agro-climatic conditions (94).

Prophylactic interventions, vector control and germplasm improvement for sustainable Phytoplasma management

Detection of *Phytoplasma* infection in an accurate manner and on time is crucial for disease management (Fig. 10). Currently, there is no effective cure for these infections. Control responses for phytoplasma diseases depend on preventive and other integrative strategies. Phytoplasma diseases are agriculturally important diseases and limited control measures are available in India. The use of different concentrations of tetracycline antibiotics-controlled

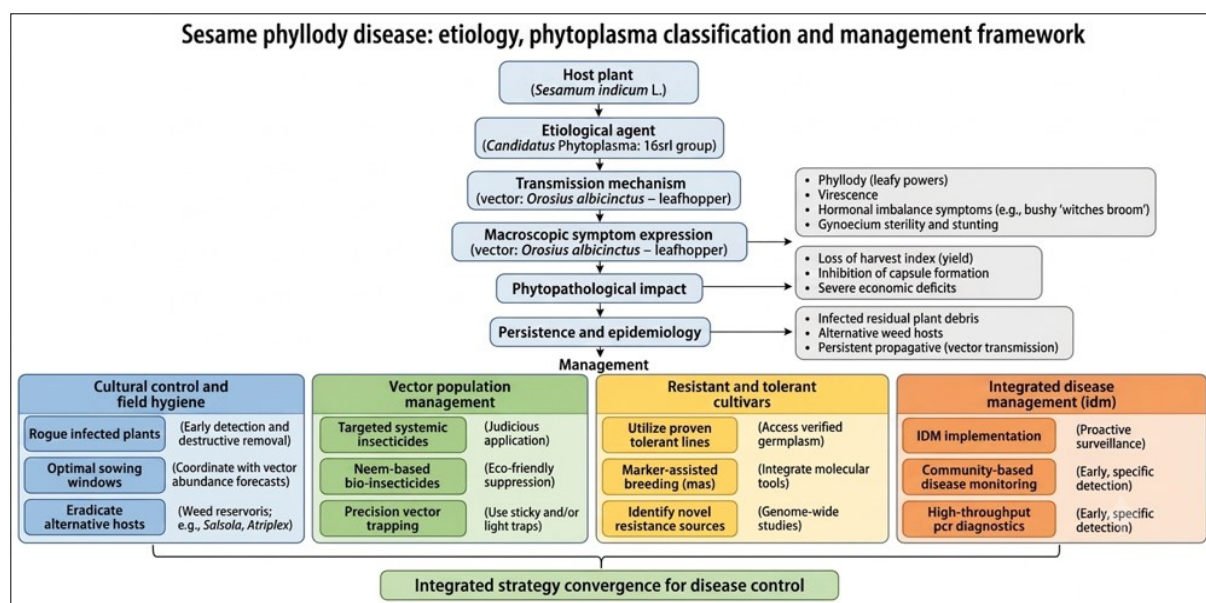


Fig. 10. Comprehensive overview of sesame phyllody disease complex: etiology, impact and management.

symptoms as well as reduced the populations of phytoplasma of brinjal (*Solanum melongena* L.), *C. roseus* and *Petunia × hybrida* (Hook.) Regel in the host plants (95–98). The use of *in vitro* tissue culture techniques, especially apical meristem culture, is beneficial to sugarcane to eliminate phytoplasmas and produce clean planting material (99, 100). Vector management has also contributed to reducing disease incidence in crops such as sesame, brinjal and cluster beans (*Cyamopsis tetragonoloba*) (82, 101, 102). Furthermore, integrated approaches involving the removal of alternate weed hosts, improved crop hygiene and the enhancement of varietal resistance have been employed in disease management programmes. Moreover, the long-term and ecological sustainability of a biological control strategy is being recognised. The system can help in ecological balance instead of using only chemicals to control the spread of phytoplasma. Breeding programmes should identify and develop phytoplasma-resistant or -tolerant genotypes from diverse agro-ecological zones to facilitate the sustainable management of these diseases and support the development of resilient cultivars for India's future agricultural system.

Conclusion

Sesame phyllody is one of the major constraints to sesame production causing significant yield losses. Therefore, it needs an in-depth understanding of its symptoms, aetiology, transmission and management. For the sustainable management of the disease, an integrated approach including cultural practices, optimum sowing dates, vector management and the development of resistant cultivars will be necessary. The progress of molecular diagnostics and phytoplasma genomics improved disease detection and shed light on the interaction between host, pathogen and vector. Future studies should focus on whole genome sequencing of phytoplasmas, characterisation of effector proteins and membrane proteins and identification of molecular markers associated with resistance in order to speed up breeding programmes. New biotechnological tools such as CRISPR-Cas9 provide promising opportunities for the development of phyllody-resistant sesame lines. Furthermore, understanding vector behaviour, exploiting resistant wild relatives such as *Sesamum alatum* and promoting early-maturing cultivars may reduce disease incidence and improve sesame productivity under diverse agro-climatic conditions.

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Authors' contributions

KC conceptualised and wrote the manuscript and prepared the flow chart. MA and MS edited the manuscript. VK, MNA and DKP proofread the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT (OpenAI) as an AI-assisted tool solely for language editing, grammar correction and improving sentence clarity during manuscript preparation. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

- Bedigian D. Characterization of sesame (*Sesamum indicum* L.) germplasm: A critique. *Genet Resour Crop Evol.* 2010;57(5):641–7. <https://doi.org/10.1007/s10722-010-9552-x>
- Uzun B, Arslan C, Furat Ş. Variation in fatty acid compositions, oil content and oil yield in a germplasm collection of sesame (*Sesamum indicum* L.). *J Am Oil Chem Soc.* 2008;85(12):1135–42. <https://doi.org/10.1007/s11746-008-1304-0>
- Langyan S, Yadava P, Bhardwaj R, Vasudev S, Yadav M. Nutritional and therapeutic potential of sesame (*Sesamum indicum* L.): A review. *J Food Biochem.* 2022;46(6). <https://doi.org/10.1111/jfbc.14134>
- Mostashari M, Mousavi Khaneghah A. Nutritional and bioactive potential of sesame seeds and oil: Recent findings and implications for health. *Trends Food Sci Technol.* 2024;140:234–45. <https://doi.org/10.1016/j.tifs.2023.104245>
- Dossou J, Wang L, Liu F, Li D. Recent advances in sesame (*Sesamum indicum* L.) seed oil: Composition, oxidative stability and nutritional properties. *Food Chem.* 2023;399:133956. <https://doi.org/10.1016/j.foodchem.2022.133956>
- Wan L, Li H, Zhang Y, Chen Y, Wang Y. Antioxidant mechanisms of sesame lignans in sesame oil: Stability and bioactivity. *Food Res Int.* 2023;162:112140. <https://doi.org/10.1016/j.foodres.2022.112140>
- Agidew MG, Dubale AA, Atlabachew M, Abebe W. Fatty acid composition, total phenolic contents and antioxidant activity of white and black sesame seed varieties from different localities of Ethiopia. *Chem Biol Technol Agric.* 2021;8:14. <https://doi.org/10.1186/s40538-021-00215-w>
- Majdalawieh AF, Mansour ZR. Sesamol, a major lignan in sesame seeds (*Sesamum indicum*): Anti-cancer potential and mechanisms of action. *Eur J Pharmacol.* 2019;855:75–89. <https://doi.org/10.1016/j.ejphar.2019.05.008>
- Mili B, Sharma N, Yadav RK. Functional properties and health benefits of sesame: An update. *Int J Chem Stud.* 2021;9(3):179–83.
- Kabinda MK, Byenkya R, Mwiine FN, Okello DK. Nutritional and functional properties of sesame (*Sesamum indicum* L.) seed cake: A by-product for livestock and poultry feed. *J Agric Sci Technol B.* 2022;12(1):1–11. <https://doi.org/10.17265/2161-6264/2022.01.001>
- Sanni GB, Ezin V, Odjo T, Ahanchede A. Unlocking the promise of sesame (*Sesamum indicum* L.) industry in Africa: Economics, opportunities, obstacles and future horizons. *CABI Agric Biosci.* 2026;7(1):22. <https://doi.org/10.1079/ab.2026.0022>
- Singh S, Tiwari S, Yadav R. Agrometeorological basis of sesame (*Sesamum indicum* L.) productivity: A review. *Legume Res.* 2022;45(11):1412–9. <https://doi.org/10.18805/LR-4672>

13. Baath GS, Sandhu KS, Sharma KD. Thermal indices for predicting growth and productivity in oilseed crops: A review. *J Agrometeorol*. 2022;24(1):91–100.
14. Bakhshandeh A, Kamkar B, Zeinali E. Modelling cardinal temperatures for germination of sesame (*Sesamum indicum* L.) using nonlinear regression analysis. *Acta Agric Scand B Soil Plant Sci*. 2017;67(2):151–61.
15. Wei L, Miao H, Li C, Zhang T, Han X, Zhang H. Genetic analysis and QTL mapping of drought tolerance in sesame (*Sesamum indicum* L.). *PLoS One*. 2013;8(5). <https://doi.org/10.1371/journal.pone.0063889>
16. Akhtar KP, Saleem MY, Asghar M, Haq MA. Sesame phyllody: A disease of economic importance in Pakistan. *Phytopathology*. 2009;99(6)–5.
17. Vasudeva RS, Sahambi HS. Studies on the phyllody disease of sesamum. *Indian Phytopathol*. 1955;8:31–6.
18. Georgiev G, Stamatov D. Influence of harvesting methods on yield losses in sesame. *Sesame Safflower Newsl*. 2005;20:10–3.
19. Moazzami AA, Kamal-Eldin A, Andersson R. HPLC analysis of sesame lignans in foods and biological samples. *J Chromatogr B*. 2006;830(2):147–54. <https://doi.org/10.1016/j.jchromb.2005.10.038>
20. Uzun B, Arslan C, Karhan M. Fat and fatty acid composition of white and black seeded sesame (*Sesamum indicum* L.) populations grown in Turkey. *J Am Oil Chem Soc*. 2008;85(10):917–21.
21. Kalwij JM. Taxonomic revision of the genus *Sesamum* L. (Pedaliaceae). *Phytotaxa*. 2012;59(1):1–25. <https://doi.org/10.11646/phytotaxa.59.1.1>
22. Myint T, Win KT, Aung MM, Lee YI. Sesame (*Sesamum indicum* L.): A climate-resilient crop for sustainable agriculture in resource-poor countries. *Sustainability*. 2020;12(23):9856. <https://doi.org/10.3390/su12239856>
23. Kobayashi N. Cytotaxonomic studies on the genus *Sesamum* L. *Jpn J Breed*. 1991;41(Suppl 2):377–84.
24. Adeola AO, Olayanju TMA, Ayodele B. Prospects and challenges of indigenous oilseeds in Nigeria. *Int J Sci Nat*. 2010;1(2):107–12.
25. Troncoso Ponce MA, Sinha R, Chen H, Allen DK. Mass balance and carbon flux in developing sesame (*Sesamum indicum* L.) seeds. *Plant Cell Physiol*. 2011;52(2):304–18. <https://doi.org/10.1093/pcp/pcq199>
26. Bedigian D. Evolution of sesame revisited: Domestication, diversity and prospects. *Genet Resour Crop Evol*. 2003;50:779–87. <https://doi.org/10.1023/A:1025029903549>
27. Tamokou JD, Mbaveng AT, Kuete V. Antimicrobial activities of African medicinal spices and vegetables. In: Kuete V, editor. *Medicinal spices and vegetables from Africa*. Cambridge (MA): Academic Press; 2017. p. 207–37. <https://doi.org/10.1016/B978-0-12-809286-6.00008-X>
28. Miao H, Zhou Y, He Y, Li X, Wang L. Advances in sesame cytogenetics and genome evolution. *Theor Appl Genet*. 2024;137(2):321–34.
29. Wang L, Yu J, Li D, Zhou Y, Zhang J. Chromosomal groupings and genome size variation in *Sesamum* species. *Plant Genome*. 2023;16(1).
30. Yadav R, Yadav HK, Chauhan A. Genetic resources and conservation status of sesame (*Sesamum indicum* L.): A review. *Genet Resour Crop Evol*. 2022;69:1749–64.
31. Gado AA. Studies on the effects of fast neutron irradiation and sodium azide on morphological and yield parameters of sesame (*Sesamum indicum* L.) [doctoral dissertation]. Cairo: Ain Shams University; 2014.
32. Langham DR. Phenology of sesame. In: Janick J, Whipkey A, editors. *Issues in new crops and new uses*. Alexandria (VA): ASHS Press; 2007. p. 144–82.
33. Yermanos DM. Sesame breeding and genetics. In: *Sesame: Status and improvement*. FAO Plant Production and Protection Paper 29. Rome: FAO; 1980. p. 85–91.
34. Free JB. *Insect pollination of crops*. 2nd ed. London: Academic Press; 1993.
35. Mazzani CG, Malaguti G. Sobre una enfermedad del ajonjolí (*Sesamum indicum*) en Venezuela. *Agron Trop*. 1952;2:155–9.
36. Ramanujam S. Occurrence of phyllody in wild sesame. *Curr Sci*. 1944;13:164.
37. Thirumalaisamy PP, Rajendran G, Gopalan A. Genetic diversity and phytoplasma association in wild and cultivated species of sesame. *Phytopathogenic Mollicutes*. 2023;13(1):44–52.
38. Singh D, Baranwal VK, Jain RK. Detection of sesame phyllody phytoplasma using a PCR assay and DNA sequencing. *J Phytopathol*. 2007;155(3):134–7.
39. Tan CM, Li CH, Tsao NW, Su LW, Lu YT, Yeh HH. Phytoplasma effector SAP11 alters plant development and defenses by destabilizing class II TCP transcription factors. *Plant Physiol*. 2015;169(4):2516–25.
40. Ji X, Dong Y, Shiran B, Talbot MJ, Edlington JE, Hughes T, et al. Control of abscisic acid catabolism and 9-cis-epoxycarotenoid dioxygenase expression in barley drought tolerance. *Plant Physiol*. 2009;150(2):575–88.
41. Ustun H, Kirdat AA, Erturk H, Sahin F. Phytoplasma effectors: Molecules that manipulate host plant processes. *Biotechnol Biotechnol Equip*. 2017;31(5):997–1006.
42. Krishnaswamy MA, Jayarajan R. Estimation of loss in sesame due to phyllody disease. *Madras Agric J*. 1983;70(1):50–2.
43. Kolte SJ. *Diseases of annual edible oilseed crops*. Vol. 1: Rapeseed-mustard and sesame diseases. Boca Raton (FL): CRC Press; 1985.
44. Verma BR, Daftari SN. Studies on the influence of phyllody disease on the oil content of sesame. *Oil Crops Newsl*. 1985;2:22–4.
45. Singh RK, Yadav AR, Srivastava JP. Effect of phyllody disease on growth, yield and oil content of sesame. *J Oilseeds Res*. 2023;40(1):59–64.
46. Esmailzadeh-Hosseini SA, Azadvar M, Salehi M. Transmission of sesame phyllody disease by the leafhopper *Orosius albicinctus* (Distant) in Iran. *Commun Agric Appl Biol Sci*. 2007;72(3):755–9.
47. Nabi SU, Phookan A, Hazarika LK. Transmission and identification of phytoplasma associated with sesame phyllody in Assam, India. *Indian Phytopathol*. 2015;68(3):298–302.
48. Phookan A, Nath PD, Bora D. Identification of *Hishimonus phycitis* as a vector of sesame phyllody phytoplasma under Assam conditions. *J Entomol Res*. 2019;43(1):17–20.
49. Trivellone V, Dietrich CH. Evolutionary dynamics of phytoplasma-vector interactions. *Insects*. 2021;12(2):124. <https://doi.org/10.3390/insects12020124>
50. Kirdat K, Tiwarekar B, Sathe S, Yadav A. From sequences to species: Charting the phytoplasma classification and taxonomy in the era of taxogenomics. *Front Microbiol*. 2023;14:1123783. <https://doi.org/10.3389/fmicb.2023.1123783>
51. Wei W, Trivellone V, Dietrich CH, Zhao Y, Bottner-Parker KD, Ivanauskas A. Identification of phytoplasmas representing multiple new genetic lineages from phloem-feeding leafhoppers highlights the diversity of phytoplasmas and their potential vectors. *Pathogens*. 2021;10(3):352. <https://doi.org/10.3390/pathogens10030352>
52. Singh D, Baranwal VK, Jain RK. Characterization of phytoplasma associated with sesame phyllody and its genetic variability in India. *Phytoparasitica*. 2016;44(1):1–13.
53. Chen W, Li Y, Wang Q, Wang N, Wei W. Recent research progress on phytoplasmas and their insect vectors in China. *Front Agric China*. 2011;5(1):54–61.

54. Sertkaya G. Transmission of sesame phyllody phytoplasma by grafting and dodder (*Cuscuta campestris*). Turk J Agric For. 1999;23(1):153–6.
55. Akhtar M, Dey U, Ghosh SK. Phytoplasma associated with phyllody disease of sesame (*Sesamum indicum* L.): Detection and characterization by PCR. J Plant Prot Res. 2009;49(1):15–21.
56. Ranebennur H, Rawat K, Rao A, Kumari P, Chalam VC, Meshram N, et al. Transmission efficiency of a 'Candidatus Phytoplasma australasia' (16SrII-D) related strain associated with sesame phyllody by dodder, grafting and leafhoppers. Eur J Plant Pathol. 2022;164(2):193–208. <https://doi.org/10.1007/s10658-022-02550-6>
57. Phookan A, Nath PD, Bora D. Epidemiological studies on sesame phyllody and development of predictive models. J Agrometeorol. 2020;22(1):79–83.
58. Mathur RL, Verma RD. Effect of date of sowing on the incidence of phyllody in sesame. Indian J Mycol Plant Pathol. 1973;3(2):177–8.
59. Paramjit S, Arora RK, Singh H. Influence of sowing dates on phyllody disease incidence in sesame. J Oilseeds Res. 1993;10(1):142–4.
60. Vachhani JG. Some observations on phyllody disease of sesame. Indian Oilseeds J. 1945;1(3):13–6.
61. Pathak P, Pandya HM, Patel JR. Effect of date of sowing and spacing on phyllody disease of sesame under middle Gujarat agroclimatic condition. Int J Plant Prot. 2013;6(2):432–4.
62. Choudhary RK, Prasad YG. Epidemiology of phyllody disease of sesame in relation to sowing time and vector population. Indian Phytopathol. 2007;60(2):215–7.
63. Harrison BD. Role of environment and vector in the epidemiology of virus diseases. Annu Rev Phytopathol. 1983;21:385–405. <https://doi.org/10.1146/annurev.py.21.090183.002125>
64. Thirumalaisamy PP, Kamalanathan D, Dhanasekaran D. Molecular characterization and host range of phytoplasma associated with phyllody disease in sesame. Phytoparasitica. 2023;51:279–89.
65. Sellammal R, Kandasamy D, Thirumalachar MJ. Phyllody disease of sesame and its epidemiology in Tamil Nadu. Madras Agric J. 1973;60:769–72.
66. Akhtar M, Singh RK, Singh AK. Identification and management of phyllody disease of sesame in Uttar Pradesh. J Oilseeds Res. 2009;26(Special Issue):514–5.
67. Li X, Hong C, Li H, Hou S, Sun Q, Zang Y, et al. Mechanisms underlying green flower formation. Hortic Res. 2026;13(6). <https://doi.org/10.1093/hr/uhag079>
68. Lee IM, Davis RE, Gundersen-Rindal DE. Phytoplasma: Phytopathogenic mollicutes. Annu Rev Microbiol. 2000;54:221–55. <https://doi.org/10.1146/annurev.micro.54.1.221>
69. Santha Lakshmi Prasad M, Surya Prakash Reddy M, Duraimurugan P, Prasindhu K, Jawaharlal J, Ramya KT, et al. Identification of resistance sources for sesame phyllody under epiphytotic conditions in India. Genet Resour Crop Evol. 2025;72:2131–40. <https://doi.org/10.1007/s10722-024-02087-z>
70. Abraham CC, Mathew J, George MV. Studies on the phyllody disease of sesame. Agric Res J Kerala. 1977;15(1):27–32.
71. Gundersen DE, Lee IM. Ultrasensitive detection of phytoplasmas by nested-PCR assays using two universal primer pairs. Phytopathol Mediterr. 1996;35(3):144–51.
72. Christensen NM, Nicolaisen M, Hansen M, Schulz A. Distribution of phytoplasmas in infected plants as revealed by real-time PCR and bioimaging. Mol Plant Microbe Interact. 2004;17(11):1175–84. <https://doi.org/10.1094/MPMI.2004.17.11.1175>
73. Nair S, Manimekalai R, Ganga Raj P, Hegde V. Loop-mediated isothermal amplification (LAMP) assay for detection of coconut root wilt disease and arecanut yellow leaf disease phytoplasma. World J Microbiol Biotechnol. 2016;32:108. <https://doi.org/10.1007/s11274-016-2078-4>
74. Cho ST, Kung HJ, Huang W, Hogenhout SA, Kuo CH. Species boundaries and molecular markers for the classification of 16SrI phytoplasmas inferred by genome analysis. Front Microbiol. 2020;11:1531. <https://doi.org/10.3389/fmicb.2020.01531>
75. Akhtar M, Singh RK, Singh AK. Genetic variability for phyllody resistance and seed yield traits in sesame. Electron J Plant Breed. 2013;4(1):1150–4.
76. Deeley J, Sellner L, Gibb KS. DAPI staining of plant-pathogenic mycoplasma-like organisms. Phytopathology. 1979;69(5):887–90. <https://doi.org/10.1094/Phyto-69-887>
77. Manimekalai R, Manjunath KR, Suresh G. Phytoplasma diseases of horticultural crops: Diagnosis and management. J Hortic Sci. 2016;11(2):99–109.
78. Purohit DK, Nath PD, Ahlawat YS. Diene's stain technique for detection of MLOs in phloem. Indian Phytopathol. 1978;31(1):86–7.
79. Bertaccini A, Lee IM. Phytoplasmas: Plant pathogenic bacteria-III. Encycl Life Sci. 2018. <https://doi.org/10.1007/978-981-13-9632-8>
80. Rao GP, Mall S, Singh V, Mishra A, Manimekalai R. Phytoplasma diseases of crops in India: Diagnosis, distribution and management. J Plant Pathol Microbiol. 2017;8(7):1000401. <https://doi.org/10.4172/2157-7471.1000401>
81. Viswanathan R. Detection of phytoplasma in sugarcane using serological and nucleic acid-based techniques. Sugar Tech. 2001;3(1–2):9–14.
82. Rao GP, Sharman M, Mall S. Management of phytoplasma diseases in India: Current status and future challenges. Arch Phytopathol Plant Prot. 2019;52(7–8):629–43. <https://doi.org/10.1007/BF02942414>
83. Hodgetts J, Dickinson M. Phytoplasma phylogenetics based on secA and 23S rRNA gene sequences. Plant Pathol. 2010;59(4):784–91. <https://doi.org/10.1111/j.1365-3059.2010.02289.x>
84. Martini M, Lee IM, Bottner-Parker KD, Zhao Y, Botti S, Bertaccini A, et al. Ribosomal and non-ribosomal classification of phytoplasmas. Int J Syst Evol Microbiol. 2019;69(7):1787–97. <https://doi.org/10.1099/ijsem.0.003395>
85. Mishra A, Mitra S, Panda P, Ghosh S, Rao GP. Characterization of phytoplasma associated with sesame phyllody using multilocus sequence analysis. Phytoparasitica. 2019;47:447–58.
86. Mitra S, Mishra A, Panda P, Rao GP. Characterization of phytoplasma associated with brinjal little leaf disease using secY and groEL genes. Indian Phytopathol. 2019;72(2):255–61.
87. Mitra S, Mishra A, Panda P, Rao GP. Molecular identification and classification of phytoplasmas using leuS and rp genes. Arch Phytopathol Plant Prot. 2019;52(3–4):253–62.
88. Mitra S, Mishra A, Panda P, Ghosh S, Rao GP. Use of housekeeping and effector genes in molecular characterization of phytoplasmas. Indian J Agric Sci. 2020;90(12):2250–6. <https://doi.org/10.56093/ijas.v90i12.110309>
89. Panda P, Mitra S, Mishra A, Ghosh S, Rao GP. Classification and phylogenetic analysis of phytoplasmas using secA and tuf genes. Arch Phytopathol Plant Prot. 2019;52(19–20):1611–22.
90. Choudhary DK, Prasad SK. Effect of sowing time and weather parameters on phyllody disease and leafhopper population in sesame. J Oilseeds Res. 2007;24(1):111–3.
91. Kumar R, Singh B, Yadav N. Epidemiology and vector dynamics of phyllody disease in sesame under Gwalior conditions. J Agrometeorol. 2022;24(1):114–8.
92. Saravanan P, Selvarayan V. Population dynamics of sesame leafhopper and correlation with weather parameters under Tamil Nadu conditions. Indian J Entomol. 2024;86(1):68–74.
93. Seasonal incidence of phyllody disease and vector population in sesame under Bundelkhand conditions [Internet]. ResearchGate; 2021.
94. Aroma C, Mote BM, Kumar N, Varshney N. Ideal date for sesamum

- sowing to achieve optimum yield under South Gujarat, India. Asian J Biol. 2025;21(9):24–30. <https://doi.org/10.9734/ajob/2025/v21i9549>
95. Verma RS, Dubey R. Tetracycline treatment for the control of phyllody disease in sesame. Indian Phytopathol. 1978;31(1):108–11.
 96. Singh SK, Rao GP, Tiwari AK. Efficacy of tetracycline in managing phytoplasma diseases in horticultural crops. Plant Prot Bull. 2007;59(2):24–7.
 97. Taloh T, Singh S, Das M. Antibiotic therapy to reduce phytoplasma titre in *Catharanthus roseus*. Indian J Plant Pathol. 2018;36(2):265–7.
 98. Ajayakumar B, Prasannakumar MK, Shetty HS. Effect of tetracycline on suppression of little leaf phytoplasma in brinjal. J Plant Prot Environ. 2007;4(1):85–9.
 99. Mishra DK, Kumar S, Rao GP. Phytoplasma elimination from sugarcane through meristem tip culture and validation using molecular markers. Sugar Tech. 2019;21(3):387–93.
 100. Tiwari AK, Singh A, Rao GP. Elimination of phytoplasma from sugarcane through meristem culture and validation by nested PCR. Phytopathogenic Mollicutes. 2011;1(2):127–32. <https://doi.org/10.5958/j.2249-4669.1.2.018>
 101. Kumhar KC, Meena PD. Evaluation of insecticides against vector of phyllody disease in cluster bean. Legume Res. 2017;40(3):562–5. <https://doi.org/10.18805/lr.v0iOF.3547>
 102. Markad AR, Rajput DS, Ukey SP. Management of leafhopper and phyllody disease in sesame with insecticides. J Entomol Zool Stud. 2018;6(2):238–41.

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