SESAME GENOME: A BIOTECHNOLOGICAL RESOURCE TO ENSURE NUTRITIONAL SECURITY

Abstract

In the backdrop of an ever increasing human population and unpredictable climate change, ensuring food and nutritional security is among the most daunting challenges faced by mankind in the present times. Oilseed crops have a high potential to improve human diet and prevent malnutrition. Other than oil, they are good sources of protein, sugars, vitamins and minerals. Sesame (*Sesamum indicum* L.) is a highly recommended oilseed crop owing to its rich nutritional value and excellent medicinal qualities. The anti-carcinogenic, anti-oxidative and anti-inflammatory properties of sesame seeds have given it the status of a traditional health food in India. In addition to its dynamic nutritional profile, sesame can be cultivated throughout the year in *Kharif*, late *Kharif*, *Rabi* and summer season. It can tolerate a high degree of water stress making it a suitable choice of crop for climate resilient agriculture. In spite of its plethora of benefits, research interest in sesame has been on the backburner, limiting its adoption worldwide. This is probably due to many other biotic and abiotic stresses, such as water logging, adversely affecting sesame yields and the unavailability of non- shattering cultivars. However, extensive research into the vast heterogeneity of the crop and its suitability for biotechnological manipulations and marker based studies hold the answer to all these challenges in sesame cultivation. In view of this, this chapter attempts to highlight the potential of sesame as an important component of climate smart agriculture while safeguarding human health and wellbeing and aims to provide impetus for valuable biotechnological research in sesame.

Keywords : Biotechnology, genome, nutritional security, oilseed, sesame

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I. THE CONUNDRUM OF NUTRITIONAL SECURITY

Twelve thousand years ago, when humans switched from being nomadic hunter gatherers to farmers, there were only 4 million mouths to feed on the planet. The world population has, since then, grown a mind boggling 2000 times [1].

Making adequate and nutritious food available to 8 billion people on earth is no easy task. However, our farmers and agricultural scientists have more or less managed to keep pace with the increasing population, first by increasing the area under food production and then by innovative farm management practices. While the efforts to increase food production and average food consumption are both applaudable and essential, they have inadvertently encouraged only energy rich diets, with high sugar, salt and saturated fat, but negligible amounts of micronutrients, dietary fibres and important bioactive phytochemicals. No wonder, more than two billion individuals, or one in three people globally suffer from micronutrient deficiencies [2].

As a result, there has been an increase in obesity caused by a poor diet and chronic non communicable diseases (NCDs) in a sizable part of the population even when the other half of the human race faces hunger and undernutrition due to lack of access to food. Therefore, while the quantity of food produced is of utmost importance, its quality and diversity cannot and must not be neglected.

II. THE RESPONSE OF CONVENTIONAL CROPS TO CLIMATE CHANGE

Today, climate change is a major factor affecting all aspects of our lives. Food production is no exception. In the era of an ever growing population, the importance of agriculture and the impact of a changing climate on it cannot be ignored. Under the changing climate, the meteorological parameters have deviated from normal values. The precipitation pattern has changed, with fluctuations in the amount of rainfall in certain areas and uncertainty in the time of the onset of monsoon. This limits the availability of irrigation water. Even the land available for agriculture is shrinking due to rise in the mean sea level. In some climatic zones, alternation in soil properties such as soil erosion, reduction in soil organic matter, Stalinization and leaching losses may occur [3].

Since, climate is one of the key elements upon which crops depend, climate change is sure to influence food security and human health by both direct effects on yield and indirect effects on the availability of irrigation water, its quality, pests, diseases and pollination agents. The extensive use of pesticides to combat the new epidemics of either weeds, pathogens or insects, may threaten biodiversity and pose a risk of the evolution of new races of pathogens [3]. The level of CO_2 in the atmosphere influences crop biomass as well as the nutritional quality of the produce. The rising temperature or the increased frequency of cyclones threaten the fate of agriculture as most crops are very sensitive to such sudden changes in the ambient climatic conditions.

The chief cause of climate change is the increase in concentration of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbon, ozone (O_3), nitrous oxide (N_2O), and water vapour into the atmosphere. In addition to being influenced by climate change, the agriculture sector also contributes to nearly 20 %of annual rise in greenhouse gases. The main sources of greenhouse gases from agriculture are the extensive use of nitrogenous fertilisers, burning of crop residues and biomass, different soil management practices, livestock production and methane gas emitted from the paddy field and by ruminants. Agriculture, therefore, is a major source of methane and among the greenhouse gases, methane gas has the highest warming capacity that is 200 times more than that of $CO_2$and 20 times more than that of N_2O. [4].

Green revolution while boosting agricultural production led to environmental pollution, biodiversity loss, land degradation due to mono-cropping systems and excessive use of agrochemicals and natural resources. This, in the long run, has led to the depletion of traditional agricultural knowledge, a deterioration of human health in general and climate change.

For a sustainable future, it is very urgent that the agricultural systems throughout the world adapt to climate change. Some of the key strategies for this are:

- To use water more efficiently and effectively. The best way to do this is by switching to less-thirsty crops. For example, rice farmers may switch to maize or legumes.
- Improve soil health. This can be done by reducing the tilling of soil, crop rotation, use of cover crops, instead of leaving the fields fallow.
- Increasing biodiversity. Mixed cropping, intercropping, cover cropping etc. are some of the important components of agricultural biodiversity.

It can be inferred from the above that there is a need to switch to diverse crops instead of the now prevalent mono-cropping practices. These crops must be hardy so that their yields buffer the fluctuating food production due to the changing climate. Therefore, the diversification of food crops holds the answer to both the problems of nutrition deficiency in the world and threat to food availability due to climate change. This will also encourage the consumption of healthy and sustainable diets comprising of locally available and low cost coarse grains, fruits and vegetables, nuts, pulses and oil seeds. Such foods are not asenergy-intensive and have a carbohydrate threshold .

III. TRADITIONAL FOOD CROPS FOR CLIMATE SMART AGRICULTURE

Climate-smart agriculture (CSA) aims to enhance food production in a sustainable manner, while increasing the adaptation and resilience of crops to climate change and reducing the amount of greenhouse gases emitted during agricultural production [6].

As elaborately explained in the sections above, in recent years, the global food consumption patterns have centred on only a few species of crop plants. Globalisation, industrialisation, urbanisation, homogenisation of agriculture products and climate change have culminated in a global food crisis. Both land and water resources have been diverted to other uses leading to declining agricultural productivity and higher food prices [7].

The loss of agrobiodiversity has made the food system very vulnerable. The consumption of homogeneous diets everyday has resulted in many chronic diseases such as obesity, deficiency diseases and metabolic syndromes [8]. Therefore, the human population is in need of alternative food sources. This is why orphan/neglected/traditional/underutilised crops have grabbed the limelight owing to their high nutritional values, exiting natural variability and contribution to agrobiodiversity [9].

Future Smart Food (FSF) are defined as neglected and underutilised species (NUS) that have high potential as they are rich in nutrients, resilient to climate change, adapted to local environmental conditions, economically feasible, and are available locally. Future Smart Food are indispensablein our fight against hunger and malnutrition [10]. For an NUS to be called a FSF, it has to meet the following criteria [11]:

- Nutrient dense,
- Climate resilient (e.g. requires minimum inputs, promotesresilience to climate change and is beneficial for the environment, for example by reducing soil runoff and erosion),
- Economically viable (e.g. generates profits and reduces drudgery) and
- Locally available or adaptable.

An example of traditional NUS are the humble Pseudo cereals such as *Chenopodim quinoa* which is gluten free and has a very high mineral and protein content and has thus caught worldwide attention recently. Millets, root crops such as yams, sweet potatoes, have also recently gained popularity for having high essential amino acids, vitamins and minerals.

Climate smart traditional practices are the answer to sustainable food production under a changing climate. Traditional practices should berediscovered and implemented to improve the socio-ecological integrity of agroecosystems. Traditional agriculture needs to be integrated with modern agricultural practices to achieve optimum food production for a lasting period of time [12].

IV. OILSEEDS IN INDIA

Oilseeds, especially in the Indian economy, occupy a very important position. The export earning potential of oilseeds amounts to billions of dollars every year. But domestic demands are still met through imports, resulting in high prices. In these post pandemic years, there is a rising trend in health and wellness internationally. People are now more conscious of their consumption patterns and the demand for healthier food options is increasing.

It can be predicted that the international demand for oilseeds will increase further for direct consumption, processed and value-added products, and also for use as superfoods with immense health benefits.

This is because oilseeds like soybean, groundnut, sesame etc. are good sources of proteins, vitamins, minerals and sugars, apart from oil. They are thus highly recommended for human nutrition and have a major role to play in a healthy balanced diet. They are especially rich in vitamins A, D and E. Oilseeds and their products are particularly important sources of polyunsaturated fatty acids (PUFA). Therefore, oilseeds have a significant role to play in nutritional security owing to their multifaceted uses.

Vegetable oil consumption is anticipated to double by 2030. But most oilseed crops have low and unstable yields. This, superimposed with the changing climate and the increasing demands emphasise the need to encourage the production of underexploited but high potential oilseed crops that are hardy, sustainable and high in nutritional value.

Such an oilseed crop that ticks all the four criteria of a Future Smart Food by the FAO is sesame.

V. SESAME

Sesame, (*Sesamum indicum* L.), better known as '*Til*' in Hindi, is believed to have been cultivated in India since time immemorial. It is considered the 'queen of oilseeds' owing to its high oil content. The oil has a characteristic nutty aroma and flavour [13]. Sesame seeds are a storehouse of vitamins and minerals and its oil holds an important position in the Hindu belief and culture. In many Asian Countries tradition, sesame is recognized as a health food [14], so much so that consuming sesame seeds on the Hindu festival of Makar Sankranti is believed to bring good health. Since sesame is amongthe oldest oilseeds known to humankind, these rituals must have some scientific basis, which have now been proven. It is recommended to consume sesame seeds during winter to boost immunity and bathing with sesame oil is good for the skin and hair.

Thus, sesame can be considered to be a traditionally, economically and nutritionally important oilseed crop.

1. **Taxonomy:** More than 38 species of the genus *Sesamum* have been described. Depending on their geographic distribution, cytogenetic and morphological information these species are classified into different groups [15].

   India is rich in the diversity of sesame. The cultivated species is *Sesamum indicum.* Apart from this,India is home to six wild species of sesame. One of them is the closest wild relative of the cultivated *sesame, S. malabaricum.* It.It has the same chromosome number as *S. indicum* (2n=26).

   The other wild species of sesame found in India are, an intermediate species complex, *S. mulayanum* (2n = 26), *S. prostratum*, *S. laciniatum* (2n = 32) and the two introduced African species, *S. radiatum* (2n = 64) and *S. alatum* (2n = 26) [16]. *S. alatum* and *S. radiatum* are consumed as vegetables in Africa, *Sesamumprostratum* has medicinal value for skin diseases. *S. radiatum* is an ornamental plant, which also has uses in soap making and green manuring.

   The taxonomic hierarchy of sesame is as given in Table 1,

Table 1: Taxonomic hierarchy of sesame [17]

Kingdom	Plantae
Subkingdom	Viridiplantae
Infrakingdom	Streptophyta

Superdivision	Embryophyta
Division	Tracheophyta
Subdivision	Spermatophyta
Class	Magnoliopsida
Superorder	Asteranae
Order	Lamiales
Family	Pedaliaceae
Genus	*Sesamum*
Species	*Indicum*

2. **Botany:** Sesame is an erect, annual herb having chromosome number 2n=26. It has an indeterminate growth habit. It is essentially a short day plant. But it can grow in long day conditions as well. Sesame has a tap root system. The stem is either round or square. As is the characteristic of the Pedaliaceae family, leaf arrangement in sesame is opposite or the upper leaves are arranged spirally and the flowers are borne generally at the axillary position. Leaves are ovate to lanceolate and have pointed apices. Based on branching, the plants are of erect to semi-erect type.

   Sesame flowers are of different colours such as white, red, violet or maroon. They have four functional epipetalous stamens and acampanulatecorolla. The lower corolla lobe is longer as compared to the upper one [18]. The epipetalous condition of sesame ensures self-pollination.

   The colour of sesame seeds ranges from cream-white to charcoal black but it is predominantly white or black. The colour variation in some sesame seeds includes red, brown or yellow [19]. The sesame varieties which are having seed colour as white, yellow and black are believed to be of superior quality and are popular in the West and Middle East, and at the same time in the far East both black and pale coloured sesame seed varieties are valued more. The different varieties and ecotypes are adapted to diverse ecology [20].

3. **Origin and history:** The cultivation of sesame in Asia is very ancient. "Sesame" or Sesamum is probably derived from the Arabic name "semsen" or "simsin,". Sesame is widely distributed in the tropical and subtropical regions of the world [21].

   Reference [22] proposed that India received sesame from Sunda Islands, a group of islands in Indonesia, during pre-Aryan times. Charred sesame seeds have also been isolated from Harappa, which is a part of the Indus Valley civilization [23]

According to researchers sesame has a polytypic origin and the basic centres of origin are India, which includes North Indian Plains, Burma and Abyssinia, which consists of Somalia and Eritrea. He considered Central Asia which consists of Afghanistan, Tadzhikistan, Uzbekistan and West Pakistan as another centre.

Researchers have reached the conclusion that sesame was probably domesticated in India for the first time. They have found evidences that domesticated sesame and the South Indian native *Sesamum malabaricum* havemorphological and cytological affinities [26].

4. **Agronomic requirements:** Sesame is mostly cultivated in the tropics and subtropics. A well-drained light to medium textured soil such as sandy-loam is most suitable for sesame cultivation. It can be cultivated throughout the year in *Kharif*, late *Kharif*, *Rabi* and summer season. The optimum temperature required for normal growth of a sesame plant is 25°C-35°C. However, at both high (> 45°C) and low (< 15°C) temperatures yield is reduced. High temperature affects pollen fertility. A well cultivated sesame crop may yield up to 1200-1500 kg/ha and 800-1000 kg/ha under irrigated and rain fed conditions respectively.

   In India sesame is mostly grown in marginal and sub marginal land areas, with limited inputs and only rain fed irrigation. This is the primary reason attributed its low yield in India. However, it is noted that using improved varieties and different farm management technologies, it may be possible to increase the yield in various agro ecological conditions in the country [27].

VI. OVERVIEW OF CURRENT SESAME PRODUCTION

Most of the sesame in the world is produced in Asia and Africa. India is one of the largest producers of sesame in the world. However, it lags behind in productivity.

In India, the average yield of sesame is 413 kg/hectare. This is very low as compared to the world’s average yield of 535 kg/hectare. However, China has managed to achieve a yield of up to 1,234 kg/hectare, which highlights the yield potential of sesame under proper management conditions.

The total area under cultivation, production and productivity of sesame in India during 2009-10 *Kharif* season were 19.420 lakh hectares, 5.885 lakh tonnes and 303 kg/ha and that during 2019-20 *Kharif* were 16.226 lakh hectares, 6.575 lakh tonnes and 405 kg/ha. This data shows decrease in the area under sesame over the years, but an increase in the production and productivity [28].

In India nearly all states are currently growing sesame in varying quantities. In the year 2021, West Bengal led both in production and productivity. Other major Indian states cultivating sesame are Gujarat, Rajasthan, Uttar Pradesh, Tamil Nadu, Madhya Pradesh and Andhra Pradesh.

India exports the largest quantity of sesame in the world. The global market for sesame is projected to have a CAGR (compound annual growth rate) of 2.2% over 2022-2027 [29]. Therefore, there is a need to enhance the production of sesame in India.

VI. USES AND NUTRITIONAL PROFILE OF SESAME

Sesame holds the potential to play a vital role in human nutrition. In times of famine in Africa, it has played a crucial source of nutrients [30]. The main nutritional composition of sesame is given in Table 2.

Table 2: Main Nutritional Components of Sesame [31]

Component	Value
Major Nutrients (g/100g)	
Fat	49.7
Fatty Acid (Poly)	21.8
Crude Protein	20.8
Fatty Acid (Mono)	18.8
Protein	17.6
Fibers	14.9
Carbohydrate	9.85
Fatty Acid (Saturated)	7.09
Starch	4
Sugars	3
Micronutrients (mg/100g)	
Calcium	962
Phosphorous	605
Potassium	468
Magnesium	324
Iron	14.6
Zinc	5.74
Sodium	2.31
Copper	1.58
Manganese	1.24
β Carotene (µg/100g)	5
Vitamin B1	79
Vitamin B2	25
Vitamin B3	4.52
Vitamin B5	5

Vitamin B6	79
Vitamin B9 (μg/100g)	97
Vitamin E	25

Most often, sesame seeds are utilised for oil extraction or they are consumed as a whole in the form of candies and *laddu*s. After oil extraction, the cake obtained is mostly used for as manure and livestock feed.

Sesame oil has long keeping quality as it contains sesamol which is an antioxidant that prevents oxidative decay. The diversified use of sesame oil can be noted for its use in the manufacture of soap, perfumes and pharmaceuticals. Sesame oil is a storehouse of fatty acids. 96% of the total fatty acids in sesame oil is composed of oleic acid (43%), linoleic acid (35%), palmitic acid (11%) and stearic acid (7%) [32]. In *Ayurveda*, sesame seeds have been describedas the seeds of immortality.

Sesame seeds serve as a vault of energy, minerals and vitamins. They are a rich source of vitamin A, B complex and E. They are also rich in many important minerals like phosphorus, iron, calcium, potassium, magnesium, zinc and copper. It is believed that especially in the case of milk allergies, sesame is the best substitute for mother’s milk. Sesame seeds are a repository of amino acids such as methionine and tryptophan.

Sesame has high nutritional value as it contains sesamin, sesamolin, PUFA, tocopherols, phytates and other phenolics which are health promoting and biologically active compounds. The root is having chlorosesamone which has antifungal activity [27]. Sesame flower extract has a tumour inhibiting effect.

Sesame fat holds great importance in the food industry because of its characteristic flavour, stability and high-quality cooking value. The oxidative stability and antioxidant properties are attributed by sesamin and sesaminollignans in thenon-glycerolfraction [33]. It has been confirmed that the lignans present in abundance in sesame seeds, have a considerable antioxidation activity which is beneficial for the human body. The antioxidants check the process of oxidation by binding to the oxidative radicals. These can be taken as dietary supplements to combat serious diseases like cancer.

Apart from these, sesame is also used in pharmaceuticals, soaps, cosmetics and lamp oil. It contains high value secondary metabolites such as lignans, flavonoids, saponins and phenolic compounds of high value. It also has potential use in biodiesel production [34].

Because of these reasons, the demand for sesame has been rising for international trade in recent years and India needs to keep up its production and productivity by efficient management practices and varieties to retain its place in the global market.

VIII. SESAME AS A PART OF CROPPING SYSTEMS

Sesame is a short duration crop and thus is suitable as a part of many cropping systems. It can also be used as a sequence crop or a catch crop. There are several evidences of enhanced productivity of such sesame based cropping systems.

Many sequence cropping and intercropping systems have been found to be profitable to farmers [35].

Moreover, it was found that even under abnormal rainfall conditions during a major part of the growing season, sesame + groundnut – castor, sesame + green gram – castor, sesame – castor, sesame + hybrid cotton showed high productivity. They encouraged the diversification of crops and insisted that this could protect the farmers against the uncertainties of the changing climate and help them achieve greater productivity and profitability. It has been found that the extensive root system of sesame plant goes deep into the soil and conditionsit, reducing cotton root rot and root knot, thus increasing the yield of the ensuing cotton crop [35].

IX. EXISTING GENETIC RESOURCES IN SESAME

It is well known that wild relatives of crop plants serve as essential sources of novel adaptation traits and genes to improve agricultural production, especially under the changing climatic conditions. They are indispensable for crop improvement against biotic and abiotic stresses. India, China, Central Asia, the Middle East, and Ethiopia have been proposed as five centres of genetic diversity for sesame [36].

Sesame seeds are recalcitrant which makes the conservation of germplasm difficult. Inspite of this, a significant variability of genetic materials of both the cultivated and wild relatives of sesame are being conserved in gene banks across the world. The countries with gene banks holding a significant proportion of sesame genetic diversity are India, China,South Korea, the United States. Some small-scale gene banks in some Asian and African countries also conserve sesame germplasm.

These extensive collections have allowed the constitution of sesame core collections. These help in better utilisation of the novel genetic variation and also facilitate planning of effective exploration strategies [37]. The Oil Crop Research Institute of the Chinese Academy of Agricultural Sciences has a core collection of sesame. India is also maintaining core collections of sesame germplasm at the National Bureau of Plant Genetic Resources (NBPGR), India with the help of International Plant Genetic Resources Institute (IPGRI) [16].

The National Gene Bank at NBPGR, New Delhi holds 9630 accessions of sesame stored for long term conservation in cold modules. As many as 255 *Sesamum* species are conserved at the cryobank at NBPGR [16, 37].

Wild species of sesame have been reported to possess several useful characters that can be used in crop improvement programmes. It has been found that wild relatives of sesame possess higher harvest index than the presently cultivated species. This character can be used to improve the cultivated lines of sesame. Wild species also have some traits that contribute towards better yield such as multilocular capsules, bold seeds, high seed retention capacity. They also have desirable growth characteristics such as determinate growth habit, early maturity, photo and thermal insensitivity anduniform ripening. Wild species have also in the past contributed to increasing the nutritional value of sesame, contributing genes high oil, protein and other secondary metabolite contents. They are also used for reducingthe anti-nutritional factors present in domesticated sesame.

Wild sesame species also contribute genes for tolerance to different biotic stresses such as pests and diseases. This has been used in the past for obtaining resistance to*Phytophthora* blight, *Alternaria* leaf spot,*Cercospora* spot, leaf curl virus, phyllody etc.Various abiotic stress such as drought, waterlogging and salinityresistance genes are also present in wild species of sesame [16]. *S. malabaricum*has been found to be tolerant to waterlogging whereas *S. occidentale*is drought tolerant. *S. radiatum* on the other hand is resistant to *Fusarium* wilt.

The great variability found in Sesame implies that many of these wild species may be very useful as parents in hybridization programs to develop sesame varieties with improved traits.

X. EVIDENCES OF ADAPTION OF SESAME TO CLIMATE CHANGE

Sesame is a hardy crop. It can grow well in even harsh environments with minimum input requirements and without pesticides. This is because, sesame has a high level of natural tolerance for pests and diseases [38]. It is often cultivated in arid and semiarid areas where water deficit stress is quite common. This is possible because sesame has a deep and spreading root system that makes it tolerant to draught stress.

Some researchers conducted a field experiment to study the impact of deficit irrigation at four levels such as extreme, severe, moderate, and mild on oil content, yield and harvest index of sesame. They reported that the low-input oilseed crops like sesame may be grown in water stress conditions without significant reduction in the yield and oil content. Reference [40] has reported that farmers of Ethiopia consider sesame as an important crop diversification option to mitigate yield fluctuations due to the changing climate.

Some researchers had carried out an experiment in West Bengal, India in 1996 and 1997 with an objective to study the effect of macro and micro climate variation on sesame yield. They observed a positive effect on sesame yield when the ambient temperature rose above 30°C up toflowering stage. A similar increase in yield was also seen when the temperatures were increased at 50 days after emergence.

Some researchers also concluded that an increase in ambient temperatures will positively impact sesame leading to higher yields.

XI. MAJOR CONSTRAINTS TO SESAME PRODUCTION

Sesame yields are highly variable. Like most other crops, they are dependent on the variety, the cultural practices and the environmental fluctuations.

Currently, sesame is mostly cultivated in resource starved conditions. It is sensitive to water stress, salt stress and chilling injury that limit stable production [43]. It is also adversely affected by excessive calcium and sodium chloride ions in the soil. However, at germination and early stages of growth sesame has been found to be tolerant to salinity.

Many genotypes have been found to be variable for this trait [44]. Severe effects on sesame yields are seen after 2-3 days of continuous waterlogging.

In addition to the above abiotic stresses, sesame is also prone to disease and insect attack. Biotic stresses are a significant cause of yield reduction and amount to an average yield loss of 25%. *Cercospora* leaf spots, leaf blotch, wilt, leaf blight, charcoal rot, anthracnose, powdery mildew, and phyllody are the economically important diseases in sesame. Moreover, the crop is severely attacked by insect pests such as capsule borer, leaf roller, sphinx moth, gall midge and aphids [45].

The lack of suitable improved cultivars, poorly responding to inputssuch as fertilisers limit sesame production. The cultivated lines are still having wild characteristics such as profuse branching, capsule shattering, uneven ripening, low harvest index and indeterminate growth habit.These characters limit the suitability of sesame for mechanical harvesting and commercial production. Many cultivars are highly susceptible to diseasesand pests [43].

XII. BREEDING ADVANCES IN SESAME

The main breeding objectives for sesame are as follows:

- Increased yields
- Increased oil contents
- Better oil quality with high unsaturated fatty acids
- Resistance to biotic (*eg.*phyllody) and abiotic stresses (*eg.* drought)
- Uniformity
- Improving the morphological architecture of the plants
- Breeding for non-shattering type variety
- Increased nutritional quality (eg. tocopherol and lignan content)
- Short duration of crop
- High temperature tolerance
- Reduced anti-nutritional factors like phytic and oxalic acids

In spite of the multifarious dietary uses and health benefits of sesame, it still lags as compared to other oilseed crops due to a lack of research interest in this crop. Therefore, there is still enormous potential for genetic improvement in yield, oil quality, quantity and other qualitative traits.

Many different traditional breeding methods have been used to breed better varieties of sesame. These include pedigree selection, mutation breeding, intra and interspecific hybridization and heterosis breeding.

Wild varieties and landraces of sesame have been utilised for the improvement of traits such as resistance by pedigree selection. Heterosis in sesame was first reported in 1945. It was observed that the increase in yield due to hybrid vigour reached 252% in China [46]. Consequently, in 1993 the first sesame hybrid variety was released, which had 29.52% more yield than previously existing varieties [47].

A non-dehiscent cultivar was released in 1997 in the USA. In this cultivar, the capsules only opened at the tip and did not shatter. These could be left in the field for more than 50 days after maturity, and could be dried down to 6% seed moisture without any yield loss due to shattering. Nowadays, in addition to the above traditional breeding methods, relatively modern methods that can overcome the limitations of conventional breeding are also being usedin sesame breeding for example genetic transformation and *in vitro* regeneration.

Most importantly, marker assisted selection and the use of next generation sequencing has greatly enhanced the efficiency of breeding methods in sesame. Many different molecular markers have been applied, such as, RAPD, AFLP, SSR, ISSR, ESTs, SNPs etc. These have been used to understand the genetic basis of morphological traits such as closed capsule trait and growth habit [48].

XIII. INSIGHTS INTO THE SESAME GENOME

The application of advanced sequencing and high throughput genotyping in sesame have led to the generation of much genomic resources which include whole genome sequences, transcriptomic sequences and genetic maps.

A group in the Oil Crop Research Institute of the Chinese Academy of Agricultural Science first sequenced the sesame genome [49]. The genome assembly of an elite cultivar of India, Swetha, has also been created by scientists of NBPGR, India. It is of 340Mb making it the largest genome assembly of sesame till date [50]. Genome wide association studies (GWAS) will open new avenues in functional and comparative genomic studies through marker assisted selection (MAS) and genomic selection. Clear phylogenetic relationships between cultivated and wild relatives of sesame may be established, resulting in their efficient utilisation in crop improvement programmes. We will be able to identify genes and QTLs associated with biotic and abiotic stress tolerance. The breeding values of various traits may be calculated which will help achieve the breeding objectives of sesame faster and with more accuracy.

Large scale marker development by specific locus amplified fragment (SLAF) sequencing has enabled the construction of a high-density genetic map of the sesame genome. This will be helpful for genotyping of the many characters of sesame and even for *de novo* SNP discovery. This has allowed the efficient development of many polymorphic markers in a very short time [51]. Such studies have enabled map based gene isolation through fine mapping of the sesame genome. These have opened new avenues in molecular breeding of sesame.

The complete cDNA library of developing sesame seeds has been generated resulting in 41,248 ESTs [52]. Comparative analyses of ESTs were conducted in the developing seeds of *Sesamum indicum* and *Arabidopsis thaliana* as a result of which genes responsible for seed storage products accumulation and lignans biosynthesis were identified in sesame [53]. Studies for the identification of homologous genes in sesame involved in oil biosynthesis based on conservative transcription factors such as LEC1 (LEAFY COTYLEDON1), PKL (PICKLE), WRI1 (WRINKLED1) have been carried out.

Similar understanding of the genetic basis of any character of interest, is a powerful tool for future breeding advances in sesame.

Sequencing can help identify nucleotide binding sites and leucine rich repeats encoded by pest and disease resistance genes. For this online functional databases are also now available for breeding programs in sesame such as Sesame Genome Database (Sinbase) and Sesame FG.

XIV. BIOTECHNOLOGY AND SESAME

Until recently, crop development programs in sesame have depended mostly on conventional breeding. In view of the current increasing importance of this oilseed crop in the food, health and cosmetic industry, a biotechnological approach for its revitalization can be very beneficial [54].

Various biotechnological techniques can be successfully employed in sesame such as MAS, genome editing, RNA interference (RNAi), transgenic technology etc. [55].

The revolutionary genome editing technique Clustered Regularly Interspaced Short Palindromic Repeats(CRISPR)-Cas9 can precisely modify specific genes. The genomic data collected in sesame can be utilised for the application of CRISPR-Cas9 for targeted trait improvement. In sesame [56] successfully generated sesame with edited SiPDSand SiPDR genes. These genes are known to be involved in the carotenoid biosynthesis pathway.

RNAi can be used for the suppression of undesirable gene action and to study gene function. Some scientists [57] in 2016 used RNAi to alter seed coat pigmentation in sesame by silencing the SiMYB56 gene.

Such examples of the use of such techniques in sesame are currently limited but organised research and extensive use has huge potential to improve sesame varieties. The need is to integrate biotechnology with genomic approaches such as GWAS and genomic selection. An excellent example of such a synergistic approach for sesame breeding was shown by [58] who first combined GWAS with genomic selection for the identification of QTLs to improve sesame yield and quality. They then utilized CRISPR-Cas9 technology to target and edit genes involved in the regulation of seed size, oil content, and fatty acid composition. The integration

XV. CONCLUSION

Sesame is an ideal crop of sustainable agriculture having high productivity potential and ability to grow on research poor lands. It can play a key role in our fight against climate change and global nutrition deficiency. This is possible only when farmers all over India find it economically profitable to cultivate sesame in their fields. If the varieties available to farmers are better yielding, climate hardy, grow with minimum attention and can give assured returns in spite of the vagaries of nature, they are sure to be adopted by farmers. This task of developing such varieties needs the corroborated efforts of all the stakeholders, farmers, agricultural researchers, the government and the private sector. The integration of the available diversity, molecular resources, modern crop management technologies can play a crucial role in efficient sesame breeding. Integrated multidisciplinary research efforts including genomics, biotechnology, physiology, biochemistry with conventional breeding is needed for efficient sesame breeding. Gene editing technologies are the future for breeding in sesame. Sesame, if properly adopted, has the potential to ensure a stable return from farming, especially for vulnerable small scale farmers.

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