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SCIENTIFIC CORRESPONDENCE

Sugarcane Genetic Resources for Challenged Agriculture

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Abstract
Sugarcane agriculture is frequently challenged across the globe by biotic and abiotic factors causing significant damage to production and productivity. Sugarcane germplasm by virtue of its exhaustive collection, extensive characterization and evaluation exhibits an ideal system for combating the challenges offered from various stresses. The genus Saccharum consists of six species: *Saccharum officinarum*, *S. spontaneum*, *S. robustum*, *Saccharum edule*, *S. barberi* and *Saccharum sinense*. *S.officinarum* 'the noble cane' a native of Pacific islands is the basic genetic material where all the commercial hybrids are built up on. Along with the noble canes, the wild species *S. spontaneum* which has a Mediterranean and Indian origin has contributed significantly to the development of present-day commercial hybrids providing resistance to various biotic and abiotic stresses. From a utilization point of view, the sugarcane gene pool is very attractive due to less intra- and interspecific barriers and even intergeneric gene transfer involving *Sclerostachya, Erianthus* and *Miscanthus, Sorghum and Imperata* is viable. The sugarcane crop has a history of very systematic germplasm collection efforts from the beginning which has resulted in the collection of large variability of both cultivated and wild genetic resources through various national and international expeditions. In India, the gene bank at Kannur, Kerala, which is an internationally recognized systematically maintained gene bank for the sugarcane germplasm, houses the largest collection of sugarcane germplasm. A total of 3377 accessions are maintained at Kannur and over 3000 accessions at Coimbatore. The germplasm has been periodically screened against various biotic and abiotic stresses and resistant/tolerant accessions have been identified. These clones are the potential sources for genetic improvement of sugarcane against the threat posed by the challenges for sugarcane agriculture. This paper reviews the status of sugarcane germplasm collection in India and the sources of resistance to various biotic and abiotic stresses available in it.

Keywords Sugarcane · Germplasm · Biotic stress · Abiotic stress · Resistance · Utilization

Introduction

Plant genetic resources are the backbone of any crop improvement programme for sustaining production and productivity. Sugarcane agriculture is frequently being challenged across the globe by biotic and abiotic factors causing significant damage to production and productivity. In India, recent years of surplus production of sugarcane led to policy changes including enhanced blending of alcohol with petroleum products and licensing for direct conversion of alcohol from sugarcane juice. This has opened up new challenges to produce more sugarcane for first-generation ethanol also with higher biomass for 2G ethanol. To sustain sugarcane agriculture, increasing farmers' income is yet another challenge in sugarcane agriculture which can be addressed with value addition and product diversification. By virtue of its exhaustive collection sugarcane germplasm, extensive characterization and evaluation and exuberant utilization pose an ideal system for combating the challenges offered from all corners. The cultivated sugarcane *Saccharum officinarum* originated in Pacific islands and moved to different parts of the world between 1100 AD and 8000 BC (Artschwager and Brandes 1958) through different routes. *S.officinarum* was believed to be moved from the centre of origin to the Indian subcontinent through Indonesia and

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Burma, simultaneous with spreading to other part of Asia. It is believed to be entered the eastern region of the country in Assam and moved further into the north-eastern region and spread to the subtropical and tropical part. During the course of migration, genetic introgression has taken place resulting in the development of *Saccharum barberi* which was under cultivation in North India before man-made varieties were brought under cultivation. The genus *Saccharum* consists of six species, viz. *S. officinarum* L*, S. spontaneum* L., *S. robustum* Brandes and Jeswiet ex Grassl, *Saccharum edule* Hassk., *S. barberi* Jeswiet and *S. sinense* Roxborough (Hodkinson et al. 2002; Paterson et al. 2013). The wild species *S.spontaneum* is well distributed from New Guinea to Africa, the Mediterranean and India as the centre of origin (Mukherjee 1957; Roach and Daniels 1987). *S. spontaneum* has contributed significantly to the development of present-day commercial hybrids providing resistance to various biotic and abiotic stresses. The sugarcane crop is very fortunate to have a history of very systematic collection efforts that started as early as the history of sugarcane cultivation. This resulted in the collection of a large variability of both cultivated and wild genetic resources from various national and international expeditions and conserved very systematically by maintaining genetic purity in the field gene bank. For effective utilization of genetic resources in any crop improvement programme, well-characterized and documented genetic resources are the prerequisite.

The gene bank at Kannur, Kerala, India, is such a systematically maintained gene bank for the sugarcane germplasm which is internationally recognized. The gene bank at Kannur started with the international collections acquired based on the resolution of the International Society of Sugarcane Technologists (ISSCT) in 1956. Further, Indian subcontinent and the adjoining countries were thoroughly explored through 34 exploration trips till 2020 and collected a large number of wild species of *Saccharum* and allied genera. In addition to it, the Indian hybrid collections and the exotic hybrid collections received under bilateral agreements were also added to the collection. It houses the largest collection of sugarcane germplasm including the different species of *Saccharum*, commercial and historical hybrids developed in India and other sugarcane-growing countries, and also the related genera. From a utilization point of view, the sugarcane gene pool is very impressive as intra- and interspecific barriers are very less and even intergeneric gene transfer is viable and being exploited. Intergeneric hybrids involving *Sclerostachya, Erianthus* and *Miscanthus* can be made with ease and in relatively large numbers (Sreenivasan et al. 1987). The allied genera such as *Sorghum* and *Imperata* also hybridize with *Saccharum* and could contribute to genetic improvement of sugarcane.

Collection

The origin and domestication of sugarcane (*S. officinarum*) was in the Malayan Archipelago (Brunei, East Timor, Indonesia, Malaysia, Papua New Guinea, the Philippines, Singapore, Christmas Island and Cocos Islands) or Melanesia or Polynesian Islands by selection from wild canes with a clear centre of diversity in New Guinea (Mukherjee 1957). Maximum collection of *S.officinarum* was made from New Guinea (Daniels and Roach 1987). The sugarcane migrations started pre-historically to the various centres of diversity along with human migration, and the tracks of migration (Fig. 1) were elaborated by Artschwager and Brandes (1958). The centre of diversity for *S.robustum* and *S.edule* also attributed to New Guinea. The origin of *S.barberi* and *S.sinense* was in eastern India by hybridization between *S.officinarum* and *S.spontaneum* (Parthasarathy 1946). *S.spontaneum* has the diversity, extended from Japan, Indonesia, New guinea, India to the Mediterranean and Africa (Panje and Babu 1960). Mukherjee (1957) suggested that 'Saccharum complex' (*Saccharum, Erianthus, Narenga, Sclerostachya*) has originated most probably in the region of common frontiers of India, Burma and China. The wild sugarcane (Saccharum spontaneum) and related wild genera such as *Erianthus, Narenga and Sclerostachya* occur abundantly in this region. The efforts on organized international collection programmes for sugarcane germplasm were extensively described by Berding and Roach (1987). In India, a directed approach to the collection and conservation of germplasm in sugarcane was started by Barber in 1912. He was successful in collecting 112 North Indian sugarcane clones for comparative evaluation and selective introduction. Subsequently under the 'Spontaneum Expedition Scheme' launched in 1948, 605 *S. spontaneum* clones from India, other Asian countries and Africa were collected. The promising clones developed in the breeding programme in the country and the clones obtained from similar breeding programmes of other countries were added to the collection subsequently. Based on the resolution of the International Society of Sugarcane Technologists (ISSCT), in 1956 the Sugarcane Breeding Institute, Coimbatore, was recognized as a centre for world collection of sugarcane germplasm besides the one at Canal Point and Miami, Florida, in the USA. The clones from the world collection of sugarcane maintained by USDA in Miami, Florida, were also introduced in the next few years to Sugarcane Breeding Institute. Indian subcontinent and the adjoining countries were thoroughly explored, and 34 exploration trips were conducted since 1912. North-east India comprising Meghalaya, Manipur and Arunachal pradaesh and Himalayan states, viz. Himachal paradesh and Utharakhand, are the hot spot for *S.spontaneum* diversity so as the related genera, viz.

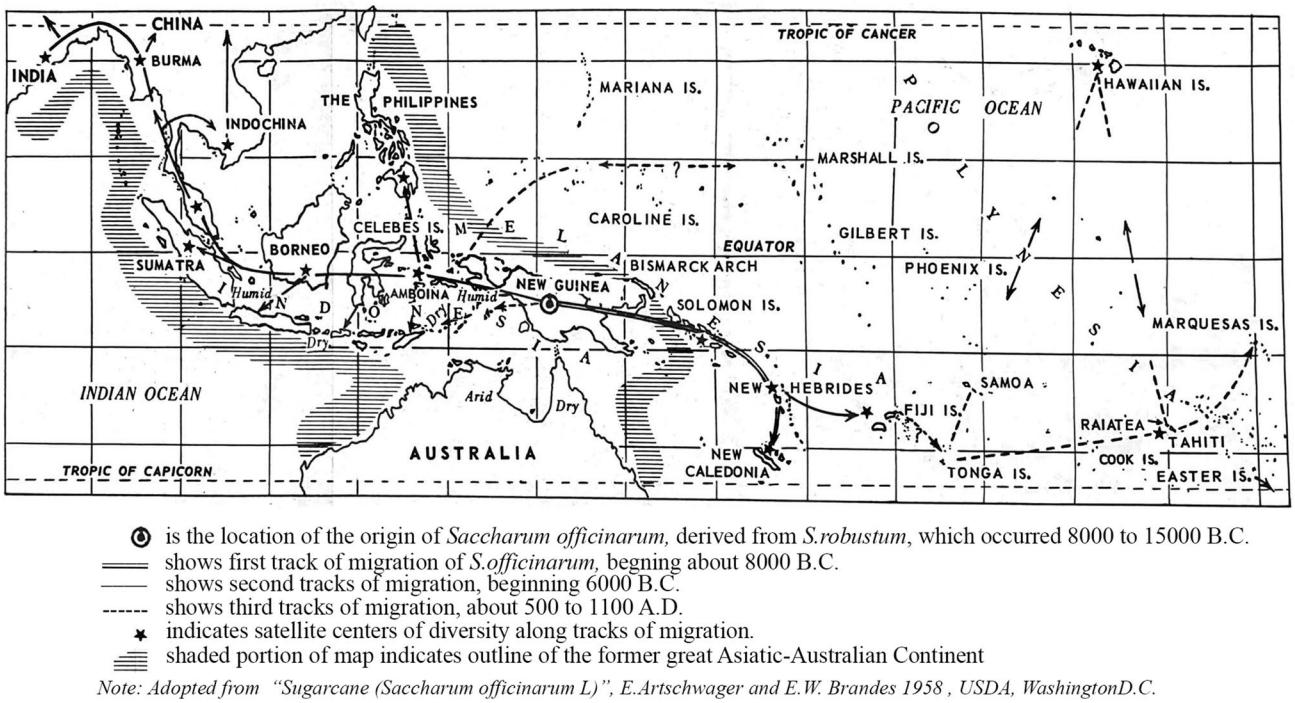

Fig. 1 Origin, migration and diversification centres of noble sugarcanes

miscanthus, Narenga, Sclerostachya and Erianthus. This region shows ample of variability for morphological and agronomical traits (Nair et al. 1991, 1993 and 1998; Govindraj et al. 2010), and many accessions collected from high altitude are the potential source for winter tolerance.

Conservation

The exploration efforts are followed meticulously by the conservation efforts to make available the genetic resources for present use and for posterity. From 1962 onwards, the world collection of sugarcane germplasm is maintained at Sugarcane Breeding Institute Research Centre, Kannur (Cannanore), which was established mainly for this purpose. The germplasm introduced from other countries, especially under ISSCT agreement, commercial and historical hybrids obtained subsequently as a result of germplasm exchange and hybrids developed in India were the initial genetic resources at the field gene bank. Indian expedition resulted in amassing a large number *of S. spontaneum* collections along with a few collections of *S. officinarum* and wild-related genera (Amalraj et al. 2006). Starting from 1912 to 2020, the expeditions covered almost all the states of the Indian subcontinent. The germplasm collection made since 1985 is maintained at ICAR-SBI, Coimbatore.

The germplasm accessions are maintained in the field by clonal replanting every year. The Kannur Research Centre of ICAR-SBI has located away from sugarcane commercial plantations, and cereals like maize and sorghum are also not cultivated in the nearby areas. This helped to maintain the germplasm with minimal incidence of diseases and pests. The unique location advantage like tropical conditions with temperature ranges between 18 °C and 37 °C, annual rainfall ranging from 3000 to 4000 mm, and the availability of good quality water for irrigation throughout the crops season and absence of extreme weather factors make it suitable for maintaining the gene bank for sugarcane. The germplasm is monitored regularly for diseases and pest incidence and also for flowering. The germplasm accessions maintained at Kannur Gene bank are free from major sugarcane diseases such as sugarcane mosaic and red rot and continued to maintain free of these two diseases by adopting strict quarantine measures. The overall flowering of the clones under natural condition in the field gene bank for *S. officinarum* is less than 25%, and maximum percentage in a given year is 15.7%, so as the case for *S.robustum* (23.4%), *S.barberi* (28.6%), *S.sinense* (6.7%), exotic hybrids (42.8%), IA clones (93.8%), *E.arundinaceus* (29.6%), allied genera Indian collection (68.4%), *S.spontaneum* Exotic collection (69.6%) and IND collection of *S.spontaneum* (24.2)% (SBI Annual Report 2022). The present status of the sugarcane germplasm assembly maintained at Research Centre Kannur and Main Institute Coimbatore is listed in Table 1.

In addition to this, over a hundred clones were maintained under in vitro conservation (SBI Annual Report 2020), and

Table 1 Sugarcane germplasm collections at ICAR-SBI. (Source SBI, Annual report 2022)

Clone/species	No. of accession maintained	
	Kannur	Coimbatore
S. officinarum	757	–
S. robustum	127	–
S.edule	16	–
S. barberi	42	–
S. sinense	30	–
S. spontaneum	384	1706
Foreign hybrids	614	52
Indian hybrids and others	1035	1984
IA clones	130	13
Allied genera and others	240	533
National active germplasm	–	291
Total	3375	

a duplicate core set of 200 *S.officinarum* clones were maintained at ICAR-SBI Research Centre, Agali, Palakkad.

Utilization

The best example of germplasm utilization in an agricultural crop may be attributed to sugarcane on accounts of the availability of the gene pool, the exhaustiveness of characterization, evaluation and documentation, the plasticity of sugarcane genome to accommodate the chromosome even from wild-related genera and over 100 years of systematic breeding programme. Inter- and intraspecific hybridization programme in sugarcane has been initiated as early as 1858, soon after the report of sexual reproduction in sugarcane (Heinz and Tew 1987). Several mating systems are reported for sugarcane breeding of which proven cross and proven parent-based progenies are generally practised.

Intergeneric hybridization in sugarcane also received the attention of sugarcane breeders as early as 1913 (Barber 1916) with a success in crossing *S. officinarum* with *Narenga porphyrocoma.* Several scientists attempted intergeneric hybridization involving different species of *Saccharum* with genera like, *Narenga, Sclerostachya, Miscanthus, Erianthus, Sorghum, Imperata* and *ZEA*. Attempts were also made to hybridize sugarcane with bamboo (Venkatraman 1937; Loh et al. 1951; Raghavan 1952; Rao et al. 1967) with limited success in incorporating the traits. Crosses have been made to produce hybrids between *Saccharum* and *Narenga, Sclerostachya* (Barber 1916; Parthasarathy 1948; Kandasami 1961). Many progenies with intermediate in most of the vegetative characteristics like early flowering, early maturity, high tillering and erect growth habit, resistant to red rot, smut, mosaic diseases and resistant to waterlogging were incorporated by distant hybridization.

Over 2800 hybrid Co canes have been developed over a period of 100 years in the country which shows the extensive effort put on germplasm utilization for crop improvement. Many of these have become popular varieties in different parts of the country and even outside the country. The first interspecific hybrid produced in India in 1912 between 'Vellai' (*S.officinarum*) and the wild species *S.spontaneum* was the earliest demonstration of the use of wild species in crop improvement in sugarcane. Some of the landmark varieties developed are Co 205, Co 312, Co 313, Co 419, Co 527, Co 740, Co 997, Co 62,175, Co 6304, Co 6907, Co1148, Co1158, Co 7805, Co 7717, Co 8903 and Co 86,032. These varieties have played a significant role in sustaining the growth and expansion of the sugarcane cultivation across India. The variety released in 2000, Co 86,032 occupy most of the sugarcane area of tropical India. Recent varieties released from the institute include Co 99,004, Co 0403, Co 2001–13, Co 2001–15 for the tropics; Co 98,014, Co 0237, Co 0238, Co 0118 and Co 5011 for the subtropics; and Co 0232 and Co 0233 for north-east and north–central India. The recent spread of Co 0238 in subtropical belt has resulted a sea change in the production and recovery of sugar in this area. With the collaborative support and by extending the national hybridization facility with 20 state sugarcane research stations across the country, several outstanding varieties like Co C671, Co J64, CoS 767, CoS 8436, Co J83, CoPant 84,211, CoSe 92,423, CoSe 95,422, CoS 88230, etc. were developed.

Challenges to the Sugarcane Agriculture

Biotic and abiotic stresses and cost of cultivation are major challenges of sugarcane agriculture (Chandran et al. 2022). Enhanced utilization of germplasm is the key to combat the challenges offered by biotic and abiotic stresses. The long duration of breeding cycle, the complexity of polyploidy level, high-degree-of-heterozygosity linkage drag during wide hybridization and limited financial and manpower resources were reported as the bottlenecks in germplasm utilization (Mahadevaiah et al. 2019). To increase the farmer's income and to efficiently divert the surplus production of sugarcane, product diversification plays a crucial role. In addition to the energy canes, there are many technologies for value-added products from juice, bagasse and molasses are available. To maximize the production of these novel compounds, the diversity available in the germplasm is to be churned out judiciously.

Sources for Diversified Products

Other than conventional products, requirement of ethanol, A1 quality jaggery, inflorescence as vegetable, good quality fresh juice and various food products from sugarcane juice demands evaluation and identification of superior canes for different qualities.

Energy Canes

The germplasm collection of the wild sugarcane species, *E.arundinaceus, w*as evaluated (Amalraj et al. 2004) for its performance under cultivation, biomass production, stalk yield, fibre content and juice quality. Out of 88 clones evaluated, 23 clones with high fibre–pith ratio were identified. The *Erianthus* clone SES 159 was identified superior for bagasse yield 53.4% and fibre yield 25.4% and good source for high fibre content (Subramanian et al. 2005). The production of ethanol directly from juice also demands varieties with higher juice and sugar content and demands better variety specific to ethanol production. National policy on biofuel proposes to scale up the blending to 20%, the estimated ethanol requirement for fuel, potable and industrial use would be 20,000 million litres by 2050, and this will increase demand by 400% more production of sugarcane (ICAR-SBI Vision 2050). The increase in area in sugarcane production is very minimal, and hence, the rapid development in the field of 2G ethanol from lignocellulosic feedstock will be a new area where the genetic resources of sugarcane may offer much. Incorporation of climate resilience from the diverse gene pool with high biomass production will expand the area of cultivation. The development of type 1 (SBIEC 11001, SBIEC 11002) and type II (SBIEC 11003, SBIEC 11004) energy canes (SBI Annual Report 2011–12) shows the importance of wild species and allied genera to exploit the marginal land for enhancing the area of cultivation without sacrificing the sugarcane area.

Jaggery

Jaggery is rich in important minerals which can be made available to the masses to alleviate the problems of malnutrition and undernutrition. It also contains the vitamins and minerals present in sugarcane juice and is known as the healthiest sugar in the world. Jaggery consumption is gaining more attention as a healthier sweetener compared to white sugar. The juice quality, sugar content and jaggery-making quality were studied extensively, and genotypic differences in yield and quality were reported. Several genotypes were identified which give A1 quality jaggery. In the production process of jaggery itself, modified methods of preparing liquid jaggery without any chemical additives and powder form jaggery with organic clarificants (Malavika and Chandran 2021; Ribisha and Chandran 2021) also demand genotypes with better juice qualities. Liquid jaggery from *S. officinarum* clones was found to possess better palatability and is rich in iron and calcium content. The recovery of liquid jaggery ranged from 6.1% (*S. robustum*) to 20.5% by weight of juice (in high-sugar genotypes *S. officinarum*).

Vegetable

The aborted inflorescence of *S. edule* is a delicacy in pacific islands, and the aborted inflorescence looks like a miniature maize cob and can be eaten as a salad or cooked. An evaluation was conducted to assess the yield potential of 9 *S. edule* clones available in the germplasm, and IJ 76–338 was the prolific yielder with 100% flowering shoots and by weight of inflorescence NG 77–10 (Chandran et al. 2014). The inflorescence can be used for edible purposes, and biomass can be used as feedstock for energy production or in the paper pulp industry.

Anti-Oxidants

In a study of screening of *S.officinarum* clones with different rind and leaf colours for antioxidant content, 57 NG 77, 28 NG 78 and 57 NG 37 were reported to have a high ascorbic acid content, and 57 NG 77(str), Fiji 30 and Fiji 38 for high phenolic content and total antioxidant content 57 NG 77(str), NG 77–92 Gastrep preanger, HM black, Fiji 28 and NG 77–18 (SBI annual report 2009–2010). The Red fleshed *S.robustum* was also studied for its antioxidants, polyphenol and ascorbic acid content, and clones (NG 77–73, NG 77–75, NG 77–76, NG 77–78, NG 77–84, NG 77–88, NG 77–90, NG 77–132 and 28 NG 219 NG 77–132) were identified as potential sources of antioxidant content (SBI Annual Report, 2011–12). Among the 459 progenies developed by a polycross on *S.robustum* with red flesh, eight progenies (GUK 14–129, GUK 14–130, GUK 14–732, GUK 14–754, GUK 14–69, GUK 14–30 and GUK 14–41) were having gradation of flesh colour from red to white and significantly superior for biomass yield- and yield-related traits to NG77-84 and one progeny GUK 14–48 was with red flesh, similar to female parent but superior for biomass yield and extraction percentage (SBI Annual report 2022). These clones are the potential sources of high antioxidant content with improved quality traits.

Juice

For **t**he direct consumption of juice and also for preserving the juice, varieties with better juice content and quality are in demand. The *S. officinarum* clones with better refreshing quality are more suitable for chewing, direct consumption

of juice as well as for preservation by freezing with natural additives (Dhanya 2022).

Sources of Resistance to Various Biotic and Abiotic Stresses

Diseases

Diseases are a major threat to sugarcane cultivation. In India, more than 50 important diseases have been reported in sugarcane causing a reduction in yield and juice quality (Viswanthan and Rao 2011). It is estimated that 10 to 15 per cent of losses in sugarcane are caused by diseases. Major diseases in sugarcane germplasm are red rot, smut, wilt, rust, pokkah boeng, yellow leaf disease (YLD), mosaic, sugarcane bacilliform virus disease (SCBV), grassy shoot and ratoon stunt disease. Ring spot, brown spot, brown stripe, yellow spot, banded sclerotial disease and eye spot are the minor diseases reported in sugarcane and cause loss depending on the weather conditions. Germplasm is regularly used for breeding programme for the improvement of various characteristics including disease resistance (Viswanathan 2018). Among the species of *Saccharum*, *S. spontaneum* in particular has played a crucial role in sugarcane breeding programmes and to impart tolerance or resistance to various biotic and abiotic stresses in sugarcane varieties (Sreenivasan and Amalraj 2004). The contribution of the two clones 'Coimbatore' and 'Glagah', of *S. spontaneum*, is worth mentioning for figuring prominently in the pedigree of many Indian hybrids. The first commercial interspecific F1 hybrid, Co 205, released for subtropical zones in India, was obtained by crossing the *S. officinarum* clone 'Vellai' as the female parent with the *S. spontaneum* clone 'Coimbatore'. The targeted breeding programmes for diseases was mainly revolving around the major disease red rot, and in the recent past, rust and smut resistance are also looked at as additional traits to be considered in the selection process. Varieties used in imparting resistant traits in the early period were Co 419, Co 453, Co 603 (pistil parent) for smut, Co 475, Co 980, Co 1227 for red rot, CB 38–22 for leaf scald, Co 475 for leaf scald, red rot and mosaic, Co 290 for leaf scald, gumming disease, fiji disease and mosaic resistance and Co 449 for yellow leaf spot disease (Machado and Burnquist 1986; Shrivastava and Srivastava 2016). Singh et al. (2017) reported SES 594 was resistant and Cayana, CP 33–130, CP 44–43, BO 28, Kheli, Malani, POJ 2946, Ramsal, TUC 521 were moderately resistant to red rot. Baragua, Koelz 11,131, Koelz 11,132 of *S. officinarum*, 28 NG 251, 57 NG 238 of *S. robustum*, Chin, Dhaur Kalig, Kansar, Maneria IMP-1552, Mungo 254, Nargori, Kewali-14 G, Manga (SIC) of *S. barberi*, Reha, Ikhri and Kalkya of *S. sinense* showed consistent resistance against red rot (Viswanathan et al. 2017). The potential of *S.spontaneum* clones for conferring stable resistance to red rot (Balasundaram et al. 2001) and *Erianthus arundinaceus* clones as additional sources of resistance (Premachandran and Balamuralikrishnan 1998) shows the importance of these species in crop improvement programme of sugarcane.

Red rot

Red rot caused by *Colletotrichum falcatum* Went is one of the important diseases which cause severe yield reduction in sugarcane and it directly affects the economic part of the plant and (Viswanathan et al. 2017). Red rot occurs in 77 countries across all the sugarcane-growing continents (Singh and Lal 2000). In India, red rot is prevalent in most of the sugarcane-growing states at varying intensities (Viswanathan 2010). Extensive studies related to resistance and screening of sugarcane clones were carried out in India. Sreenivasan and Nair (1991) reported that Baragua, Saipan G, Seleri, 28 NG 266, 57 NG 77 from *S. officinarum* were resistant to red rot. Governor, Green German, Keong, Selemi Bali, 28 NG 12, 28 NG 34, 51 NG 22, 51 NG 45, 51 NG 131 sport, 57 NG 67 N Str., 57 NG 77 N Str., 57 NG 78 Red, 57 NG 203, 57 NG 237, IJ 76–551, 57 NG 137 and 57 NG 140 were moderately resistant. Among *S. barberi* collection, Lalri, Agoule, Dhaur Kinara, Kansar, Pararia-257 and Pathri were moderately resistant to red rot. In *S. sinense*, Archi showed a moderate resistance reaction to red rot. In *S. robustum*, 57 NG 238 is moderately resistant (Ramana Rao et al. 1985). Viswanathan et al. (2017) screened different species of *Saccharum* from 2004–2008 by CCT and plug method against CF06 (Cf671) isolate and reported that among *S. officinarum,* NG 77–142 as consistently showing resistance and another six clones as moderately resistant, among *S. robustum,* NG 77–3 as resistant and another 13 clones as moderately resistant, among *S. barberi* 5 clones as resistant and 10 clones as moderately resistant and among *S.sinense,* four clones as moderately resistant. Red rot resistance score of some of the clones, viz. Baragua and Saipan G, was conforming with the earlier reports.

Smut

Sugarcane smut is caused by *Sporisorium scitamineum*, which belongs to the phylum Basidiomycota. It is also prevalent in all the countries where the sugarcane crop is cultivated. The typical symptom of this disease is the development of a whip-like sorus from the top of the infected stalks, and the spores of the exposed sorus are spread by wind and rain (Comstock 2000). Smut resistance might exist in both wild and cultivated sugarcanes (Table 2) can contribute to the improvement of sugarcane through intra- and interspecific breeding programme.

Table 2 List of *S. officinarum* clones resistant/moderately resistant to smut. Source: Catalogue on sugarcane genetic resources- III S.*officinarum L.* 1991. T.V. Sreenivasan and N.V. Nair

Resistant	Moderately resistant
Ardjoena, Awela Green Sport, Bamboo, Bamboo Blanca, Batec Lupog, Big Tanna, Striped Aubin, Bandjer Masim Hitam, Bois Rouge, Branchue, Bravo de Perico, Caira, Cavengerie, China, Chittan, Fiji 15, Fiji 31, Fiji 64, Fotiogo, Governor, Green Sport, Haak Kwat Che, Hitam Broewang, Hawai Original-26, Java Hebbal, Javari Kabbu, Kaludai Boothan, Kea 21, Keong, Khajuria, Kham, Laukona-15, Lousiana Purple, Local Red, Loethers, Mauritius-131, Mia Do, Mia Voi, Mogali, Ohia-1, Oidang, Padangsche Dark Red, Padangsche Light Red, Pilimi-60, Poona, Port Makey Black, Preanger Striped, Ratgros Ventre Red Ribbon, Rood Djapara, SS 60–1, Saipan D, Striped Tip, Tamarin Re Union, Tahiti-3, Tanna, Tjepering, Tolo Fua Lau-1, Tomohon Zwart, Tonga Tabu-6, UB1, Vellai, White transparent, NC 17, NC 18, NC 20, NC 24 Dark Purple, NC 28, NC 32 Sport, NC 33, NC 49, NC 78, NC 91, NC 92, NC 99, NC 116, 14 NG 190, 21 NG 1, 21 NG 2, 21 NG 5, 21 NG 10, 21 NG 33, 28 NG 4, 28 NG 12, 28 NG 17, 28 NG 20, 28 NG 34, 28 NG 35, 28 NG 45, 28 NG 40, 28 NG 47, 28 NG 51, 28 NG 52, 28 NG 55, 28 NG 62, 28 NG 93, 28 NG 97, 28 NG 110, 28 NG 203, 28 NG 215, 28 NG 256, 28 NG 262, 28NG 266,28 NG 279, 28 NG 287, 51 NG 5, 51 NG 11, 51 NG 18, 51 NG 21, 51 NG 32, 51 NG 40, 51 NG 41, 51 NG 42, 51 NG 43, 51 NG 44, 51 NG 58, 51 NG 61, 51 NG 90, 51 NG 96, 51 NG 99, 51 NG 111, 51 NG 115G, 51 NG 115str, 51 NG, 51 NG 121, 51 NG 122, 51 NG 125, 51 NG 130, 51 NG 131 Sport, 51 NG 133, 51 NG 134, 51 NG 138, 51 NG 152, 51 NG 162, 51 NG 163, 51 NG 165, 57 NG 45, 57 NG 53, 57 NG 96, 57 NG 126, 57 NG 137, 57 NG 146, 57 NG 151, 57 NG 155, 57 NG 170, 57 NG 174, 57 NG 186, 57 NG 191, 57 NG 199, 57 NG 200, 57 NG 229, 57 NG 243, 57 NG 251, 57 NG 252, IJ 76–314, IJ 76–322, IJ 76–456, IJ 76–558, IJ 76–564, IJ 76–567, IK-76–2, IK-76–95, IK-76–108, IK-76–245, IM 76–245, IS 76–117, IS 76–225, NG 77–28, NG 77–42, NG 77–62, NG 77–70, NG 77–127, NG 77–171, NG 77–223	Aboe Amboina, Azul de Caza, Balghat Thin, Bamboo Morada, Caledonia Ribbon, Ceram Red, Chapina, Chrystalina, Fiji 28, Fiji 30, Fiji 39, Fiji 43, Green German, Hawai Original-38, Hawai Original-52, Kea 21, Mahona, Negros Purple, Pompey, Pynmana Ribbon, Ramgarh, Red Cane, Sarawak Unknown, Selemi Bali, Sepoya No. 1, Tjing Bali, Vespertina, Yellow Bamboo, NC-40, NC-51, 21 NG 9, 21 NG 31, 28 NG 10, 28 NG 14, 51 NG 12, 51 NG 18, 51 NG 65, 51 NG 73, 51 NG 95, 51 NG 97, 51 NG 101, 51 NG 123, 51 NG 126, 51 NG 131, 51 NG 145, 51 NG 26, 51 NG 31, 57 NG 49, 57 NG 131, 57 NG 147, 57 NG 161, 57 NG 175, 57 NG 177, 57 NG 182, 57 NG 196, 57 NG 209, 57 NG 240 Str., 57 NG 240 Yellow, NG 77–99

In *S.barberi*, Baroukha, Dhaur Kinara, Hemja, Kansar,Khatuia, Mankia, Mungo 237, Rekhra and Sararoo were shown resistance reaction to smut, and Kewali 14 G, Manjuria, Matna Shaj, Nargori and Pararia 257 were moderately resistant (Ramana Rao et al. 1985).

In *S. sinense,* Archi, Cayana, Kalkya, Kavangire, Maneira IMP 1648, Mcilkrum, Merthizel, Oshima, Rounda, Tekcha-Chiki-Island, Tekcha-Chung-Tseng, Tukuyu-No.1, Uba Del Natal, Uba Naquin, Uba Reunion and Uba White were resistant to smut, and Chukche, Pansahi and Tekcha were moderately resistant.

In *S.robustum,* many clones were available for resistant to smut, viz. IJ 76–293, IJ 76–414, IJ 76–417, IJ 76–426, IJ 76–435, IJ 76–470, IJ 76–481, IJ 76–482, IJ 76–489, IJ 76–494, IJ 76–496, IJ 76–499, IJ 76–507, IJ 76–534, IJ 76–535, IJ 76–546, IJ 76–547, IM 76–232, IM 76–255, IM 76–256, IM 76–258, IM 76–260, 51 NG-6, 51 NG-27, 57 NG 83, 57 NG 133, 57 NG 134, NG 77–13, NG 77–55, NG 77–57, NG 77–78, NG 77–108, NG 77–145, NG 77–148, NG 77–159 and NG 77–215 (Ramana Rao et al. 1985).

Rust

Rust is an important foliar disease in sugarcane. Two major types of rusts caused by *Puccinia* spp. were reported in India and also in other countries (Selvakumar and Viswanathan 2019). Though it is not a major disease in India, the occurrence of crop failure has been reported in isolated pockets. Severe rust epidemics on the Co 0323 in Chamrajnagar and Mysore districts in Karnataka during 2016–17 season reduced the crop yield significantly (Selvakumar and Viswanathan 2019). The following Indian hybrid clones (Co 1238, Co 1006, Co 1240, Co 1277, Co 1301, Co 1301, Co 1309, Co 412, Co 616, Co 645, Co 679, Co 688, Co 706, Co 760, Co 873, Co 892, Co 985, Co 993) and seven exotic hybrids (B 41–227, B 46–62, CP 49–50, F 46–64, H 45–2708, H 49–5, Q 33) were moderately resistant to rust (SBI Annual Report 1960–61).

Insect Pest Resistance in Sugarcane

Sugarcane is a long duration crop of 10–12 months and is liable to be attacked by a number of pests. Insect pests, viz.

borer complex, termites, pyrilla, mites, white grubs, whitefly, mealy bug and scales, are known to inflict considerable losses in cane yield as well as quality. The scenario of insect pests varies in subtropical and tropical belts of sugarcane. Top borer, shoot borer and stalk borer are found predominantly subtropical areas, whereas internodes borer and early shoot borer are prevalent in tropical region (David et al. 1986).

Though there is no separate breeding programme for insect pest resistance, the resistance to various pests was considered by selecting the parentage and the progenies in the breeding programme. The sugarcane germplasm collection and conservation programmes have been successful on a global basis and have provided a large number of accessions for use in insect resistance screening which in turn serve as valuable resources for breeding programmes. Among sugarcane genetic resources available, some of the Co-series canes show a certain level of resistance against major insect pests and have the potential could be effectively harnessed in breeding.

Internode Borer

(*Chilo sacchariphagus indicus*): Among sugarcane genetic resources available, Co-series canes, viz. CO 975, CO 7304 and COJ 46, were found to express greater level of resistance to internode borer. Further, Agarwal (1969) recorded very good level of morphological resistance expressed in Co1007, Co975, Co1049 and Co6510 against internode borer. *Saccharum* spp. germplasm plays a vital role in providing resources for internode borer resistance traits. Mahesh et al. (2018) screened 171 accessions of four *Saccharum* spp. from the world collection of sugarcane germplasm maintained at the ICAR-Sugarcane Breeding Institute Research Centre, Kannur, Kerala State, India, against internode borer and recorded 29 accessions found to be resistant based on the infestation index. Earlier studies showed that accessions, viz. Ikhri, Pansahi, Uba White (*S.sinense*), Cavangerie, NG 77–26, NG 77–62 (*S.officinarum*), Manjuria, Matanwar, Pararia N Ganj, Pararia Shaj (*S.barberi*), NG 77–55, NG 77–94, NG 77–136, NG 77–147 (*S. robustum*) (SBI Annual report 1982) and L 61–52, B 49–119, B 45–229, B 35–187, B 34–12, B 45–151, Q 63, B 43–337, PR 905, B 42–42, B 38–192, Q 69, B 45–181, B 44–131 (exotic hybrids), were showed resistant to INB (SBI Annual report 2005–06). The moderately resistant clones to INB are Co 281, Co 356, Co 449, Co 605, Co 603, Co 617, Co 658, Co 737, Co 740, Co 775, Co 791 (ICAR-SBI Annual report 1981), Co 853, Co 951, Co 955, Co 976, Co 997, Co 1157, Co 6202, Co 62,101, Co 6425, Co 6602, Co 6806, Co 7314, CoA 711, CoA 7602, CoC 671, CoC 775, CoJ 67, CoJ 270, CoL 9, CoP 2, CoS 311, CoS 673, BO 11, BO 72, BO 32, BO 47, BO 84, BO 89 and BO 90 (SBI Annual report 1981), Dhaur Alig, Dhaur Kinar, Kansar, Mungo 254. Pararia 257, Pararia, Pathri (*S. barberi*), NG 77–34, NG 77–59,28 NG-219,57 NG 83 (*S. robustum*) Chynia (*S. sinense*) (SBI Annual report 1982) and B 33–54 B 37–112, B 208, B 47–225 (exotic hybrids) (SBI Annual report 2005–06) were also reported to be moderately resistant to INB.

Pink Borer

(*Sesamia inferens*): Based on the three-year screening programme, Mahesh et al. (2015) identified 57 NG 208 57 NG 231 IJ 76–280 IK 76–64 IM 76–232 IS 76–121 NG 77–1 NG 77–13 NG 77–94 NG 77–159 NG 77–176 NG 77–213 NG 77–219 NG 77–238 IS 76–119 (*S. robustum*) resistant to Pink borer. Among *S. barberi,* Dark Pindaria, Dhaur Alig, Kansar, Kewali-14G, Mankia, Mungo-254, Nargori and Pathri were resistant, and in *S. sinense,* Agaul, Kheli and Malani were resistant.

Top borer

(*Scirpophaga excerptalis*): The *S.robustum* clones, viz. IJ 76–416, IM 76–232, NG 77–159 (SBI Annual report 2000–01), and 13 exotic hybrids clones (B 20–266, B 208, B 37–112, B 42–42, B 44–131, B 47–225, B 97–239, L 20–350, L 61–52, PR 20–239, PR 905, PR 908) were reported to be resistant to top borer (ICAR-SBI Annual report 2005–06). NG 77 13, IJ 76–258, IJ 76–435, IJ 76–536, IM 76–256, NG 77–38 and NG 77–56 were moderately resistant among *S.robustum* (SBI Annual Report 1990–91), and B 49–119, B 35–187, B 33–54, Q 69, B 45–151, B 43–337, B 45–181 and B 38–192 were among the exotic hybrids. Among Indian hybrid clones, Co 419, Co 745, Co 6516, Co 859, Co1158 and Co 7224 were resistant to top shoot borer (Satyagopal et al. 2014). It was suggested that in top borer endemic areas CoL.9 may be preferred as a resistant variety in both plant and ratoon crops (Agarwal et al.1971).

White Grub

(*Holotrichia serrata*): The following exotic hybrids hybrid clones (Q 63, Q 68, CP 44–101) and Indian hybrids (Co 955, Co 976, Co 6812, Co 6904, Co 6909, Co 6914 Co 7219, Co 7501, Co 7626, Co 7703, Co 7704, Co 7708 CoA 767, CoA 770, BO 47, BO 92 CoM 661) are reported to be resistant to white grub infestation. The *S. spontaneum* clones SES-93, SES- 124, SES 582 and SES 606 (SBI Annual Report 1996–97) were identified as tolerant to higher white grub populations.

Scale Insects

(*Melanaspis glomerata):* In case of *S. spontaneum*, two accessions, namely SH 61–4–1 and SH 61–4–3, were totally free from infestation of sugarcane scale, and 21 accessions were categorized as least susceptible out of total 79 accessions screened for two years which could be very well exploited for resistant breeding programmes against scale insect (Mahesh et al. 2020).

Root Borer

(*Polyocha depressella*): Least susceptible clones reported against root borer are PR 1070, M 76/39, POJ 2727, PR 1016, PR 1083, CP 31–394, CP 79–318, CP 70–1133, CP 98–1029, LF 05–119, LF 65–554, Q73, POJ 29–46, B 43–104, CYMA 09–1268, H 32–8560, CP 96–1602 (SBI Annual Report 2014–15).

Early Shoot borer

(*Chilo infuscatellus*): PR 1076, PT 48–1, Q 62, M 76–39, CP 57–614, Q 50, POJ 2727, MOL 251, H 59–3775, LF 63–1617, SP 81–1763, CP 98–1029, LF 05–119, LF 65–554, Q 73. B35-197, CP 56–519, BN 111 CP 44–92 CP 80–1842, H 32–8560, CP 80–1743, B 42–231, PR 1097, B 40–175 (SBI Annual Report 2014–15). For example, varieties such as Co 312, Co 421, Co 661, Co 917 and Co 853 show resistance against shoot borer.

Multiple Pest Resistance

Based on the studies at different centres, the following clones were identified with multiple pest resistance to four or more pests (SBI Annual Report 1995–1996).

Multiple Resistant to Four Pests

Dhaur Alig (*S.barberi*) for stalk borer, INB, root borer and scale; *S.robustum* clones, NG 77–136 was resistant to shoot borer stalk borer, root borer and scale; IJ 76–425 to shoot borer, root borer, white grub and scale; NG 77–145 to stalk borer, top borer, root borer and scale; NG 77–146 to stalk borer INB, root borer and scale; and NG 77–213 to top borer INB, root borer and scale. Among the *Erianthus* clones, IK 76–93 for shoot borer, stalk borer, top borer and root borer; IK 76–76 for shoot borer, stalk borer, top borer and white grub; IJ 76–392 for shoot borer, stalk borer, INB and top borer; IJ 76–384 for shoot borer, stalk borer, INB and white grub; IJ 76–327 and Timor wild for shoot borer, top borer white grub and scales; and IJ 76–370 for stalk borer, top bore, white grub and scale.

Multiple Pest Resistant to Five Pests

IM 76–258 for stalk borer, top borer, root borer, white grub and scale; IS 76–137 (*S.robustum)* for shoot borer, stalk borer, INB root borer and white grub; NG 77–159 for stalk borer, top borer, INB, root bore white grub. Among the *Erianthus* clones Eri-2798 was resistant to shoot borer, top borer, root bore, white grub and scale; IJ 76 400 to shoot bore, top bore, INB, white grub and scale and IS 76–215 for shoot borer, stalk bore, top borer, root borer and white grub.

Abiotic Stresses

Every living individual face stress from other living organisms or non-living things. The ability to thrive under stress conditions without affecting productivity makes the adaptation to such an environment feasible. Abiotic stress is caused due to the factors like temperature, water and chemicals. Moore (1987) classified the type of resistance as stress-tolerant but not avoiding, stress avoiding and tolerant, and stress avoiding but intolerant. Temperature stress can be either of the extremes (low or high), water may be either deficit (drought) or in excess (waterlogging). Chemicals may be salts and/or pesticides and herbicides that cause toxic effects to plant metabolism. The plant may be surrounded by one or more combinations of these stresses and continuous exposure make changes in the internal structure to the extent of heritable alterations. These changes make them adaptable and build resistance to such external stimuli. Breeding for improved resistance is the most economical way to surpass the production loss under adverse environments, wherein potential genetic resources play key role in developing such resilient varieties.

Cold Stress

Sugarcane is well adapted to tropical environments, but susceptible to chilling injury at low temperatures. The freezing temperature not only arrests the growth of the plant, but also reverses accumulated sucrose in the canes. High-fibre clones among the commercial varieties and selections of *S. spontaneum, S. sinense* and allied genera (*Miscanthus*) reported exhibiting high cold tolerance (Irvine 1968). Recent collections from high altitudes are likely to possess higher cold tolerance. Freezing affect the plant at different stages of growth including bud germination, tiller formation and also sugar accumulation (Moore 1987). Sugarcane is generally considered as a cold-sensitive plant. However, field observations have shown that the sensitivity of sugarcane to cold

depends upon the varieties. Du et al. (1999) demonstrated that some subtropical hybrid species are more cold-tolerant than tropical species. In most cases, plants do not suffer chilling injury until temperature drops below 10 ºC. Tiller growth and development are sensitive to chilling and freezing (Kanwar and Kaur 1977; Ebrahim et al. 1998; Jain et al. 2004). Poor sprouting of stubble buds at low temperatures is associated with a lower level of reducing sugars, reduced activity of acid invertase and higher accumulation of IAA and total phenols (Jain et al. 2007). *E. arundenaceus* clone, IK76-91 was found to contribute tolerance to low temperature. Out of 26 progenies evaluated, nine showed a significant increase in stalk length during winter months over the better standard Co 1148 and 6 clones significantly higher leaves indicating their tolerance (Bakshi Ram et al. 2001).

High-Temperature Stress

Sugarcane requires optimum temperature (32–33 ºC) for growth, productivity and yield expression and it is known to tolerate temperatures approaching 40 °C, while high-temperature injury around 45 °C is detrimental to sugarcane growth. High-temperature stress induced significant physiological and metabolic changes in all sugarcane genotypes at two stages of crop; however, formative phase was found to more sensitive to high temperature as compared to grand growth phase. As screening for high-temperature stress under natural field condition is dependent on the prevailing weather, a high-throughput approach known as 'temperature induction response' was standardized for sugarcane (Gomathi et al. 2013). Heat and drought stress are associated, and hence, their interaction determines the performance of the plants under stress. Heritable differences in heat tolerance have been reported in crops like *Zea mays* (Heyne and Brunson 1940), *Glycine max* (Maritinea 1979) *Avena sativa* (Coffman 1957) and *Sorghum vulgare* (Sullivan and Ross 1979). However, in sugarcane the effect of high-temperature stress on reproductive growth, development and phenology received comparatively less consideration (Ul Hassan et al. 2021). High-temperature exposure for 24 h affects the photosynthetic efficiency of sugarcane plants; hence, screening for high-temperature stress in the early developmental stages is the right approach (Panta et al. 2022). Reduction of individual leaf size, shortening of internodes and reduction in stem growth rate were the distinguishing growth characters in the thermotolerant sugarcane varieties (Kohila and Gomathi 2018). Metabolites like soluble protein content, total phenolic, glycine betaine and free proline content increased significantly under high-temperature stress, and the accumulation was comparatively higher in tolerant rather than susceptible varieties. Lipid peroxidation, chlorophyll *a* fluorescence, chlorophyll content (SPAD value), cell membrane injury, chlorophyll stability index, soluble protein, proline, leaf area and single cane weight were found to be potential physiological traits for screening varieties for thermotolerance (Gomathi et al. 2020; Gomathi and Kohila 2021). A study conducted by Sergio Castro-Nava et al. (2020) showed that heat tolerance based on the cell membrane thermostability can be improved using the existing genetic variability available within the commercial or experimental sugarcane germplasm and that the cell membrane thermostability test can be a useful screening procedure for selecting sugarcane genotypes that tolerate high-temperature stress.

Water-Deficit or Drought Stress

Water-deficit stress is caused by any water potential below zero (Levitt 1980). Under stress, anatomical and biochemical acclimatization occurs in plants, allowing them to survive and yield. The xeromorphic characters which have been increased under stress in quantitative terms are fixed as heritable changes, and can be used as traits for screening. Rooting pattern like deep growing rope root system and the low ratio of transpiration to absorption are characteristics of less susceptible or tolerant sugarcane clones. Leaf characteristics play a central role in drought resistance, viz. leaf size, exposure, number and structural modification in the epidermal cells like stomata, bulliform cells and cuticles. Canopy temperature depression (CRD) and drought resistance are correlated. Osmotic content and adaptation like accumulation of proline (Singh et al. 1972; Hanson and Nelson 1982) and abscisic acid as a stress hormone (Kuhnle et al. 1979) was reported to confer resistance. Kheli, ISH 107, ISH-007, ISH-135, ISH-148, ISH-261, ISH-273, ISH 58, Gunjera and ISH 111, Co 1148, Co 6415, Co 6806, Co 7717, Co 87,033, Co 93,026, Co 97,014, Co 97,017 and Co 98,016 are germplasm clones, and commercial hybrids with high water use efficiency (Vasantha 2017) were identified. Extensive screening of germplasm has been taken up to assess the performance under drought stress since 1971, and a lot of clones were identified for drought stress, mainly from Indian hybrids, Indo-American (IA) hybrids and a few species clones. In a study to characterize the root system traits, clones IND 85–490 (*S. spontaneum*), Putli Khajee (*S. barberi*) and IK 76–166 (*Pennisetum sp.*) exhibited higher cane weight under drought, along with significantly lesser reduction under control. The list of accessions identified as resistant across years are given in Table 3. The red rot and drought traits were combined and in seven progenies of Co 95,005 (S. robustum base) x CYMA 09–1369. Nair et al. (2017) reported *Erianthus procerus* as a potential source of multiple traits, viz. higher yield, red rot resistance and drought tolerance.

Table 3 List of resistant/moderately resistant clones against drought

Resistant	Reference
IA 3107, IA 3132, IA 3135, IA 3136, IA 3141, IA 3194, IA 3202, IA 3207, IA 3210, IA 3220, IA 3263, IA 3265, IA 3266, IA 3267, IA 3274, IA 3290, IA 3293 (Indo- American hybrids)	Annual Report ICAR-SBI, 1971
Co 86,011, Co 71,158, Co 8128, Co 85,013, Co 85,017, Co 85,020, Co 86,018, Co 86,023, Co 86,031, Co 86,032, Co 86,033, Co 86,035, Co 86,035, Co 86,039, Co 86,043, Co 86,250, Co 86,252, Co 96,042 (Indian hybrids)	Annual Report ICAR-SBI, 1990–91
Co 88,016, Co 91,027, Co 91,001, Co 91,005, Co 91,006, Co 91,011, Co 91,012, Co 91,018, Co 91,022, Co 91,023, Co 91,028, Co 91,030, 91,049, Co 91,050, Co 91,053, Co 91,055, Co 91,056, Co 91,060, Co 91,062, Co 91,063, Co 91,064, Co 91,066, Co 91,071, Co 91,075,, Co 91,032, Co, 91,036, Co 91,040, Co 91,042, Co 91,043, Co 91,077, Co 91,085, Co 91,092, Co 91,097, Co 91,103, Co 91,111, Co 91,112, Co 91,115, Co 91,117, Co 91,118, Co 91,120, Co 91,122 (Indian hybrids)	Annual Report ICAR-SBI, 1992–93
Co 89,003, Co 91,004, Co 91,008, Co 91,009, Co 91,010, Co 91,013, Co 91,015, Co 91,019 (Indian hybrids)	SBI Annual Report 1995–96
Co 94,019, Co 95,003, Co 97,009, Co 97,010 (Indian hybrids)	SBI Annual Report 2002–03
Baroukha, Dhauralig, Kewali Manga(SIC), Nargori, Pathri (*S. barberi*) IJ 76–534, IK 76–100, NG 77–136, NG 77–56, NG 77–75 (*S. robustum*) SES 103, SES 108 B SES 151 B, SES 155 A, SES *S. spontaneum* Kalkya, Khadia, Khaki, Kheli, Tekcha Chung Tseng (*S. sinense*) 57 NG 186, 57 NG 66, 57 NG 77, 57 NG 78, IJ 76 418 (*S. officinarum*) Co 8213, Co 8371, Co 86,032, Co 88,006, Co 95,014, Co 95,020 (Indian hybrids) ISH 100, ISH 118, ISH 179, ISH 269, ISH 58, ISH 9 (interspecific hybrids)	SBI Annual Report 2003–04
Moderately resistant	
Co 95,005, Co 95,006, Co 95,012, Co 95,016 (Indian hybrids)	SBI Annual Report 2002–03
ISH 1, ISH 100, ISH 110, ISH 175, ISH 39, ISH 43, ISH 76, ISH 9 (interspecific hybrids)	SBI Annual Report 2001–02
Co 8011, Co 88,011, Co 88,017, Co 88,027, Co 88,028, Co 88,032, Co 88,033, CoM 88121 (Indian hybrids)	SBI Annual Report 1993–94
Co 79,218, Co 7910, Co 7914, Co 8147, Co 85,002, Co 85,003, Co 85,009, Co 85,011, Co 85,012, Co 85,014, Co 85,018, Co 85,246 (Indian hybrids)	SBI Annual Report 1989–90
Co 8415, Co 85,015, Co 86,027, Co 86,036, Co 86,004 (Indian hybrids)	SBI Annual Report 1990–91

Winter Ratooning Ability

Winter sprouting and winter ratooning ability are correlated traits, and winter sprouting index (WSI) was used for screening genotypes for winter ratooning ability (Bakshi Ram et al. 2011). Identification of high-yield, high-sugar, disease-resistant varieties coupled with better winter ratooning ability is the priority in breeding programmes at subtropical region. Ravinder kumar et al. (2022) identified clones with excellent winter tolerance including AS 04–635, AS 04–1687, IK 76–48, Gu 07–2276, IND 00–1040, IND 00–1038 and IND 00–1039, and five clones, viz. GU 07–3849, AS 04–245, Co 0238, AS 04–2097 and GU 07–3774, with good winter tolerance potential. Hybridization of *Erianthus* with sugarcane has resulted in the introgression of genes for cold tolerance and red rot (*Colletotrichum falcatum*) resistance (Bakshi Ram et al. 2001). Out of 403 sugarcane clones evaluated for ratooning ability during peak winter months in subtropical conditions of India, wherein the maximum sprouting (98.6%) was reported among *S. spontaneum* clones. In these clones, sprouting ranged from 66.7% to 100%. Among *S. barberi*, 11 out of 22 (50%) showed 100% sprouting, with a mean of 84.2%. In general, the sprouting in *S. robustum* clones was poor though they had a wider range of variation for the same (Sahi et al. 2002).

Bakshi Ram et al. (2017) identified the promising germplasm clones for winter sprouting, with excellent WSI (> 3.00) including Co 06035, Co 12,026, Co 12,027 (Indian hybrids), BM 368, BM 33–65, BM 555, BM 61/1, CP 11–61, F 133, L 62–37, LF 64–2815, LF 65–3661, Mali, PR 1013, SP 80–1816, TUC 472 (exotic hybrids). The clones reported with good WSI (2.01 to 2.99) were Co 0237, Co 0327, Co 0331, Co 06033 (released varieties), BO 91, BO 99, BO 109, BO 120, BO 137, BO 147, BO 153, Co 0118, Co 0238, Co 05011, Co 6617, Co 6811, Co 89,003, Co 89,029, Co 98,014, Co 1148, CoB 94164, CoBln 9104, CoH 128, CoH 56, CoH 92, CoJ 88, CoLk 7901, CoLk 8001, CoLk 94,184, CoP 9702, CoP 2061, CoPant 84,211, CoPant 84,212, CoPant 90,223, CoPant 99,214, CoPant 08221, CoS 00257, CoS 03252, CoS 510, CoS 767, CoS 770, CoS 8207, CoS 8436, CoS 88230, CoS 91269, CoS 95255, CoS 95270, CoS 96275, CoSe 00235, CoSe 01424, CoSe 92,423, CoSe 96,436, CoSe 98,231 (Indian hybrids) and B 42–261, LF 61–52, LF 65–4329, Q 65, Argentina, LF 63–1617, POJ 290, PR 1044, PR 1054, BM 61/1, CP 34–79, CP 84–1198, KT 367, LF 61–52, MOL 894, SP 80–185, SP 81–783, SP 81–783, BM 368, BM 555, LF 65–3661, POJ 290, B 43–238, LF 63–1617, LF 65–119, Q 65 (exotic hybrids).

Sources of Waterlogging Tolerance

Waterlogging is one of the abiotic stresses affecting cane yield and juice quality of sugarcane crop. In India, about 2.2 lakh ha area of sugarcane faces waterlogging threat especially in parts of UP, Bihar, Orissa, Maharashtra, coastal areas of Andhra Pradesh and Karnataka (Nair 2012). Srinivasan and Batcha (1963) also reported high level of waterlogging tolerance in *S.spontaneum* clones. Waterlogging occurs mainly during the monsoon season in both tropical and subtropical India. Heavy rainfall and poor drainage of water from the soil, inundation by overflowing rivers and excessive irrigation are major causes of waterlogging. Actual stress to the plant occurs when the water table rises to root zone of the crop and is saturated with water preventing root zone aeration. Sugarcane crop grows well when water table is maintained below one metre for optimum growth and development (Moore 1987). Waterlogging stress affects almost all stages of crop growth, germination, tillering and grand growth period, thereby reducing biomass yield and quality. Waterlogging at the grand growth phase is known to reduce the cane weight and number of millable canes, thus causing yield reduction at the rate of one ton per hectare for every one-inch increase in the water level in the subtropical condition (Jain et al. 2017).

Though sugarcane is fairly tolerant to waterlogging, the extent of yield and juice quality reduction depends on genotype, stage of the crop when stress occurs and the duration of waterlogging in the field per se. Several clones of *S.spontaneum, S.robustum and Narenga* are reported to be flood-tolerant (Moore et al. 1987). The ability of superior varieties to withstand waterlogging is related to physiological, morphological, biochemical and anatomical adaptation. Waterlogging-tolerant varieties are able to form aerenchymatous roots that help in sustaining the biological processes under the anoxia condition (Drew 1997). Aerenchyma formation varies with the genotypes, some require waterlogging condition to produce such aerenchyma, whereas others produce it constitutively (Glaz et al. 2004). A physiological change during waterlogging includes reduced transpiration rate, reduced photosynthesis, retarded growth and stomatal closure, with adverse effect on nutrient uptake (Gomathi et al. 2015). Root system is the first plant part to be affected by waterlogging stress. Anoxia condition results in poor root development and insufficient respiration for normal functioning of roots (Sheu and Yang 1980). Poorly developed root system affect the absorption of nutrients and water (Banath and Monteith 1966). Aerotropic development of roots under oxygen deficiency and specialized aerenchymatous floating roots are also found as an inherent trait to combat the waterlogging stress in sugarcane (Venkatraman and Thomas 1929; Shah 1951; Srinivasan and Rao 1960).

Sugarcane varieties that have greater ability to develop adventitious roots are known to perform better under waterlogged conditions (Verma 2001). Aerial roots with high porosity help plants to survive the anoxia conditions due to water stagnation, partially replacing the function of older roots in the soil (Kozlowski and Pallardy 1984). The variety Co 99,006, developed from SBIRC Kannur, popularly called as 'Neeraj' is a waterlogging-tolerant check, showing stress adaptive physiology and morphological traits (Gomathi and Chandran 2009; Chandran et al. 2019). Studies conducted at SBIRC Kannur also proved that tolerant check Co 99,006 exhibited aerial roots much longer than all the test clones. Profuse development of fibrous floating roots is one of the characters associated with waterlogging tolerance (Srinivasan and Batcha 1963; Sartoris and Blecher 1949). Thin fibrous roots rather than thick ones ensure reduced path length for oxygen diffusion to the respiring tissues (Eavis 1972). Negatively geotropic roots with aerenchyma (Shah 1951) and enhanced intercellular spaces in adventitious roots were found to be associated with clones that are tolerant to waterlogged conditions (Verma 2001). Premachandran (2006) identified Co 62,175 as a good female parent to develop waterlogging-tolerant clones based on progeny evaluation tests. Genetic correlation of root traits under waterlogging which shows that selection for adventitious roots development may not increase sugar yield (Sukchain and Dhaliwal 2005). However, aerenchyma development is a useful criterion for the selection of waterlogging-tolerant clones (Gilbert et al. 2007). Waterlogging stress is known to reduce the juice quality traits due to inversion of sucrose, thus reducing the sugar content of the clones (Gomathi and Chandran 2013). One of the high-yield varieties under waterlogging condition Co 62,175 with more area of aerenchyma tissues exhibited inferior juice quality traits. Studies on various adaptive characters of sugarcane clones to waterlogging stress indicate that the variety Co 99,006 a waterlogging-tolerant clone had profuse and long aerial roots on the node. The variety Co 62,175 with high intensity of aerial roots had the highest area of aerenchyma tissues in the aerial root.

Resistant clones to waterlogging: Co 785, Co 8231, Co 62,175, Co 513, Co 805, Co 815, Co 900, Co 958, Co 1290, Co 62,100, Co 62,136, Co 62,197 (Indian hybrids), B 54–142, CB 40–13, CP 49–50, CP 63–361, H 49–134, H 50–7209, H 52–3683, H 53–263, Q 61 (exotic hybrids) (SBI Annual Report 1980).

Moderately resistant to waterlogging: Co 997, Co 6304, Co 294, Co 303, Co 330, Co 366, Co 378, Co 402, Co 430, Co 431, Co 513, Co 517, Co 527, Co 552, Co 563, Co 604, Co 638, Co 687, Co 692, Co 693, Co 705, Co 805, Co 815, Co 900, Co 908, Co 986, Co 992, Co 1018, Co 1090, Co 1097, Co 1151, Co 1290, Co 62,098, Co 62,100, Co 62,101, Co 62,136, Co 62,197, Co 6516, Co 6609 (Indian hybrids),

Q 17, B 35–207, B 37–161,B 37–172, B 43–33, B 44–341, B 46–136, B 54–142, CB 40–13, CL 41–223, CP 33–243, CP 49–50, CP 50–61, CP 63–1, CP 53–97, CP 63–326, CP 63–361, CP 63–372, CP 63–377, CP 63–384, CP 73–351, L 62–37, H 44–2772, H 45–2708, H 48–2094, H 49–5, H 49–134, H 49–3533, H 50–723, H 50–7209, H 51–8194, H 52–3683, H 53–263, H 54–775, H 57–5174, H 59–3775, PR 975, PR 1093, PR 1097, D 419/33, PT 4352, NCo 334, LF 69–801, LF 69–814. The Co canes developed under the waterlogging resistance breeding programme at ICAR-SBI RC Kannur (Co 99,006, Co 96,011, Co 22,017, Co 22,020, Co 19,016) and the genetic stock registered for water logging resistance (99 WL 379) are also good source of resistance to waterlogging stress.

Bakshi Ram (2017) identified Dhaur Alig and Pararia Shaj (S,*sinense*) as resistant to waterlogging. Nair (2012) reported two *S. barberi* clones (Khari and Lalri) and ISH-007, ISH-135, ISH-175, ISH-261 among interspefic hybrids as resistant. Vasantha et al. (2017) identified CoS 94267, BO 91, Dhaur Alig, Pararia Shaj, ISH -007, ISH-135, ISH-175, ISH-261, Co 6415, Co 6806, Co 87,033, Co 89,035, Co 93,026, Co 95,021, Co 97,014, Co 97015 as resistant to waterlogging.

In a study with twenty waterlogging-tolerant clones, standard checks and species clones undertaken at ICAR-SBI RC, Kannur, Co 62,175, SEL 74/1, WL11 2263, WL11 2230, Fiji15 and SS 60/1 recorded high root length, root surface area, root volume and diameter. Under waterlogged condition, Co 62,175 showed better biomass with more roots at formative phase (SBI Annual Report 2016–17). Formation of lysigenous aerenchyma under waterlogging condition was found to have a positive correlation with cane yield, but was not significant (SBI Annual Report 2018–19). In a study to characterize the root system traits, clones Djantoer-1, IND 85–490 (*S. spontaneum*), Putli Khajee (*S. barberi*) and IK 76–99 (*Pennisetum* sp.) exhibited higher cane weight under waterlogging stress, along with significantly lesser reduction under control (SBI Annual Report 2021).

Tolerance to Alkalinity

Alkalinity is as a result of excess sodium exchangeable salt, viz. carbonate or bicarbonate. The soil will be black in colour due to the dissolution of organic matter. Alkaline soil refers to electrical conductivity (EC) less than four (EC < 4), sodium exchangeable per cent (ESP) greater than 15 (ESP > 15), pH > 8.5 and sodium absorption ratio (SAR) > 13.

B 37–172, NCo 310 (exotic hybrids), Co 449, Co 419, Co 453, Co 6304, Co 6806, Co 7704, Co 975, BO 91, BO 92, BO 96, Co 1007, Co 1253, Co 1287, Co 1307, Co 312, Co 62,101, Co 62,174, Co 62,175, Co 62,198, Co 678, Co 7201, Co 7717, Co 798, Co 853, CoA 7601, CoA 7602, CoA 7701, CoC 671, CoC 779 (Indian hybrids) were resistant and Co 775, Co 658, BO 17, BO 99 (Indian hybrids) were moderately resistant.

Salinity

Saline condition is observed in arid soils, where the sodium soluble salts is in excess, with white colour chloride, sulphate and nitrate forms. Saline condition refers to the soil with EC > 4ds/m, ESP < 15, pH < 8.5 and SAR < 13. Vasantha et al. (2010) identified 113 *S. officinarum* clones, 15 *S. robustum* clones, 12 *S. barberi* and 121 IND clones tolerant to salinity based on screening in microplots.

The resistant clones identified against salinity are 21 NG 6, 28 NG 110, 28 NG 110, 28 NG 206, 28 NG 21, 28 NG 211, 51 NG 59, 51 NG 53, 51 NG 159, 51 NG 147, 51 NG 14, 28 NG 32, 28 NG 210, 21 NG 5, 21 NG 21, 21 NG 2, White Transparant, 28 NG 68, Sinense, Pakkaveli, Oramboo, Ogles Selection, Mia Voi, Maxwell, Keong, 51 NG 12, 28 NG 87, 28 NG 80, 28 NG 72, Sarwak Unknown, Tibbomird, Zwart Cheribon, Pattacherukku, Pattapatti, Pohinia 51, Mauritius 55 Str, Zwart Manila, Mongetgayam, NC 15, 28 NG 287, 51 NG 77, 57 NG 126, 57 NG 166, 57 NG 172, 57 NG 191, 57 NG 196, 57 NG 199, 57 NG 237, 57 NG 241, 57 NG 26, 57 NG 272, 57 NG 559, 57 NG 57, 57 NG 68, 57 NG 71, 57 NG 78, 77 NG 117, 77 NG 15, 77 NG 18, 77 NG 31, 77 NG 32, 77 NG 66, Chapina, Green German, IJ 76 316, IJ 76–135, IJ 76–422, IJ 76–470, Kaloodi Bhootan, Koelz 11,132, NG 77–65, Old Jamaika, Pynmana Ribbon, Tahiti 3, NG 77 242, Rayada, 57 NG 215, 57 NG 50, Calidonia, Poona, 21 NG 12, Local Red, NC 33 and the moderately resistant clones were 57 NG 110, Black Fiji, IJ 76–315, IJ 76–316, IJ 76–418, IJ 76–522, IJ 76–556, IK 76–31, IM 76–235,57 NG 212,57 NG 222, FIJI 10, NG 21–42, NG 77–67, NG 77–70 and NG 77–92, Waxy Red.

S. barberi: Kuswar, Ottur, Khatuia 124, Pararia-257, Nargori, Mungo, Kewali, Pathri and Lalri.

S. robustum: 28 NG 219, 28 NG 251, 57 NG 201, 57 NG 231, 57 NG 68, 77 NG 10, 77 NG 117, 77 NG 136, 77 NG 160, 77 NG 167, 77 NG 221, 77 NG 237, 77 NG 26, 77 NG 34, 77 NG 55 were resistant, and NG 77–221, IJ 76–470, IJ 76–507, IJ 76–543 and NG 77–11 were moderately resistant.

S. spontaneum: IND 81–202, IND 81–46, IND 81–9, IND 81–95, IND 82–247, IND 82–254, IND 82–260, IND 82–319, IND 82–325, IND 84–400, IND 84–405, IND 84–406, IND 84–450, IND 87–404, IND 84-450A, IND 85–504, IND 85–507 were resistant, and IND 84–343, IND 84–430, IND 84–469 and IND 85–506 were moderately resistant.

S. sinense: Kahaki, Uba Seedling, Reha, Pansahi and Uba White.

Among the Indian hybrids, Co 1007, Co 1132, Co 1253, Co 312, Co 62,174, Co 62,175, Co 62,198, Co 678, Co 7717,

Co 798, Co 853, Co1307, Co7701, CoA 7602, CoC 772, CoC 779, CoC671, CoJ 46, CoL 9, BO 78, Co 7204, Co 7219, Co 7314, Co 7910, CoA 71–1, Co 7201, Co 7707, Co 8208, Co 8210, Co 8213, Co 617, Co 7601, Co 8314, Co 8347, Co 8369, Co 87,270, Co 87,271, Co 87,002, Co 89,010, Co 89,027, Co 90,010, Co 91,002, Co 91,005, Co 91,011, CoJ 86141, Co 96,011, Co 96,024 were resistant and, BO 91, Co 1163, Co 285, Co 62,198, Co 6415, Co 6904, Co 7008, Co 7201, Co 7224, Co 7321, Co 7508, Co 7707, Co 8010, Co 285, Co 7204, Co 8201, Co 8209, Co 8211, Co 8212, Co 1495, Co 6914, Co 8001, Co 8318, Co 8319, CoC 777, Co 8133, Co 8134, Co 8136, Co 8140, Co 8144, Co 8145, Co 8146, Co 8150 Co 7706, Co 7902, Co 7913, Co 8359, Co 8366, Co87267, Co, 87,272, Co 97,001 and VSI 9/20 were moderately resistant.

Vasantha et al. (2017) identified the following clones for salinity resistance including Co 98,015, Co 98,016, CoLk 8102, CoS 94267 (Indian hybrids), Dhaur Alig, Pararia (*S. barberi*) and ISH-007, ISH-135, ISH-148, ISH 175 (interspecific hybrids). IND 16–1762 was resistant to salinity and characterized for its molecular expression wherein Glyoxan I and II, Dreb NHX, salinity-related protein ABA inducer laccase, caffeic acid 3–0, cellulase synthase, pectin esterase and peroxidase were reported to be over expressed in this genotype under stress (SBI Annual Report 2020).

Chemical Stress

Chemical stress is generally applicable to weedicides' application. NCo 310 was most tolerant to the herbicide Diron. *S. spontaneum* and *S. officinarum* were susceptible, but *Sorghum bicolour* showed resistance to Diron application.

Wind Pressure Stress

Rind hardiness and fibre content and canopy size are the factors influencing wind stress. *Erianthus* species with high fibre content can resist wind pressure and can be a potential source of resistance to this stress.

Future Perspectives

Despite having a large germplasm collection and very active pre-breeding programmes, the pedigree of the successful commercial varieties can be traced back to only a few basic germplasm materials. One of the major impediments in utilization of germplasm may be the regularity and synchrony of flowering. The development of fool proof artificial flowering induction methods and facility can solve this problem to a greater extant. Having a large collection of germplasm may delay the process of selection of suitable parents with diverse genetic background and thereby slow down the utilization process. Developing a mini core collection encompassing maximum diversity with respect genetic, agro-morphological traits and stress resistance will enhance the utilization. Genomic selection and shortening the breeding cycles will speed up the pre-breeding and broadening of genetic base of the crop. On the conservation point of view, the material even within the collection is vulnerable to genetic erosion as the germplasm is maintained mainly in field gene bank that is exposed to vagaries of environment, pests and pathogens. Removing the duplicates from the wild species collection has to be taken up on war foot scale; otherwise, there is a chance to lose the most precious collection at the cost of duplicate accessions with similar genetic makeup. The strengthening of complimentary conservation strategies like in vitro conservation and cryopreservation are required to avoid genetic erosion with in the collection. The other complimentary conservation options like seed, pollen, DNA fragments, etc. need to be exploited to ensure fool proof preservation of genetic diversity under ex situ conservation.

Conclusions

Sugarcane genetic resources offer resistance to an array of biotic and abiotic stresses. The stressful situation throws severe challenges with the changes in environmental conditions and by favouring the attack of more virulent pests and pathogens. Developing climate resilient varieties and varieties resistant to biotic stresses with wider genetic base is the key for combating stressful situation. Breeding for resistance to red rot and waterlogging were widely employed in sugarcane. The main source of red rot resistance that widely used in sugarcane improvement is *S.spontaneum*. Many *S.spontaneum* clones were utilized for pre-breeding programme, but a few clones like *S.spontaneum* CBE, Mandalay, *S.spontaneum* Java only could find in the pedigree of popular commercial hybrids. The important potential source for red rot-resistant sugarcane germplasm are IJ 76–400, IK 76–78, IK 76- 88, IK 76–91, IND 90–776 and IK 76–99 (*Erianthus*), SES 14-B, *S.spontaneum* CBE, IND 82–319, IND 82–284 (*S. spontaneum)* and the breeding lines developed from them. *S.spontaneum* is speculated to possess horizontal resistance, and there is continued interest in enhanced utilization of *S.spontaneum* clones. *S.officinarum*/*S.sinense* reported to impart vertical resistance. Breaking down of red rot resistance in the popular cultivars is a challenge to sugarcane breeders. Using sources of resistance with varying degrees of resistance and diverse origin, and adopting suitable screening methods may be useful for developing varieties with stable red rot resistance in sugarcane. The variety possess resistance to multiple stresses may be a viable alternative, and such parental clones with resistance

to multiple races and multiple resistance to various abiotic and biotic stresses need to be utilized in the breeding programme. The utilization of *Erianthus arundinaceus* and *Erianthus procerus* also has high potential in red rot resistance breeding programme coupling with other stresses. Both *S.spontaneum* and *E.arundinaceus* confer resistance to waterlogging, drought and breeding for red rot resistance and may go in association with improvement in other stresses too. The important wild species for waterlogging resistance are *S.spontaneum, S.robustum* and *Erianthus.* The use of red fleshed *S.robustum* clone (NG 77–84) in pre-breeding resulted in developing lines with high biomass yield under waterlogging situation. The exotic hybrid clones POJ 2878, B34-12 and Indian hybrid clones Co 99,006, Co 62,175, Co 8231, Co 7313, Co 96,011, 99 WL 379, Co 22,017, Co 22,020, Co 19,016 were also proven parents for waterlogging resistance breeding programme. It is well known that the germplasm needs to be continuously screened against emerging stresses to identify new sources of resistance. A well-characterized and documented germplasm collection is a national asset that we can bank up on in any eventualities in sugarcane agriculture. The effort put on the collection, maintenance and characterization of sugarcane genetic resources is massive so as its attempt for utilization. Still we cannot be complacent as the pre-breeding effect is not completely translated into commercial hybrids and the genetic base of released cultivars continue to remain narrow.

Author Contributions CK reviewed the genetic resources collection conservation. MN reviewed the germplasm utilization. RG reviewed the minor diseases. BM reviewed the sources of resistance to tropical pests. DC compiled the data. M reviewed the sources of resistance to subtropical pests. A reviewed the sources of resistance to low-temperature stress. K reviewed the sources of resistance to waterlogging. GR reviewed the sources of resistance to drought. M reviewed the red rot resistance. VR edited the manuscript on sources of resistance to pests and diseases. HG edited the final manuscript.

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