Diversity of the germplasm of *Saccharum* species and related genera available for use in directed breeding programmes for sugarcane improvement

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Sugarcane is primarily a crop raised by sett cuttings. After the discovery of fertility in sugarcane seeds, attempts have been made for its improvement through concerted breeding efforts. The first phase was limited to crossing among *Saccharum officinarum* clones and the resulted hybrids although had high sucrose content, lower fibre, lacked vigour, ratooning ability and resistance to diseases. In the second phase after the realization of adaptability to diverse environs, resistance to insect pests and diseases, and tolerance to abiotic stress and ratooning ability in the indigenous canes (*S. barberi*, *S. spontaneum* and *S. robustum*), a limited number of these was used in the crossing and subsequent nobilization for varietal improvement. However, the limited use of germplasm could not sustain the challenges to the crop, so also the pace of varietal development. Realization of the fact that further incorporation of *S. spontaneum* germplasm in breeding sporadic efforts paid dividends, attempts have been made to look into the diversity for traits of agronomic interest not only in *Saccharum* species, but also in the *Saccharum* complex, i.e. in the related genera. The present study reviews the diversity available for agronomic traits in *Saccharum* species clones and related genera which could be made available for use in directed breeding programmes for sugarcane improvement for the ever-increasing need of not only of sugar but also of the energy, paper and other value-added products from sugarcane.

Keywords: Abiotic and biotic stresses, genetic resources, germplasm, prebreeding, sugarcane.

THE cultivation of sugarcane has expanded to new frontiers in recent years, due to its growing demands as energy cane for the production of ethanol and co-generation of electricity, as a source of several new value-added products such as polymers, bio-butanol and bio-kerosene along with production of sugar using this crop as raw material[1]. There are variations in the morphological and medicinal properties of some of the ancient sugarcane varieties described in *Ikshuvarg* of a celebrated Ayurvedic compendium, the *Nighantu* by Bhav Misra in 1498 (refs 2, 3) stands to its testimony. Paunda and Sadharan[3] canes (ordinary) were popular even during the reign of *Akbar the Great*. Concerted breeding efforts made for sugarcane improvement since the discovery of fertility in the seeds, were limited to crossing only among the *Saccharum officinarum* clones during the first phase. The resultant hybrids though rich in sucrose content, lacked vigour, ratooning ability and resistance to pests and diseases. After realizing the potential of indigenous canes to adapt to diverse environments, resistance to insect pests and diseases, tolerance to abiotic stress and ratooning ability, the second phase of sugarcane breeding involved interspecific hybridization between *S. officinarum* clones and other *Saccharum* species. Introduction of POJ varieties in the breeding programme resulted in many good sugarcane varieties such as Co 213, Co 244, Co 312 and Co 313, which were successful from 1920 to 1940 and helped in establishing the sugar industry of North India in the 1940s (ref. 4). However, only four clones, viz. Chunnee, Katha, Saretha and Kansar figured in the parentage of most of the commercial varieties[5]. Varieties identified for desirable traits[6] (Table 1) were used for breeding of sugarcane varieties world over, e.g. B.H. 10/12; B 208; B 37172; Co 205; Co 281; Co 290; Co 419; Co 421; CP 807; CP 44-101; D 74; EK 28; F 108; H 109; H 32-8560; M 134/32; NCo 310; POJ 312; POJ 2725; POJ 2878; PR 980; Pindar; Trojan. Some of the varieties like POJ 2878 from Indonesia, and Co 213 and Co 290 from India are present in the pedigree of most of the sugarcane varieties developed world over.

Some of the favourable varieties which could be exploited in breeding programmes include those adapted to a wide range of stress conditions[7], as given in Table 2. Besides, CoC 771 (ref. 8) and CoG 95076 (ref. 9) are tolerant to tannery effluents, Co 213 to drought, Co 975 to waterlogging, Co 6806 to water stress, waterlogging and salinity, whereas Co 7717 is tolerant to sodicity[10]. Similarly, varieties with high sugar content (>20 sucrose %

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juice at 10 months) are: Q 55, Q 58 and Q 73 from Australia; B 45285 and B 54142 from Barbados; CP 62-251 and CP 63-384 from Florida, USA; LF 687639 from Fiji; Co 62126, Co 888, Co 887, Co 62118, Co 968, Co 6709, Co 1254, Co 1287, Co 62022, Co 1199, Co 1277 from India; PR 1056 and PR 1091 from Puerto Rico and F 108 from Taiwan. Among these, B 45285 from Barbados and Co 62126, from India attained sucrose juice of 21.74% and 21.17% respectively[11]. Co 527 and Co 740 were popular due to earliness and higher juice quality, Co 419 and Co 62175 for late crushing and Co 449 was an early ripening variety which, besides being highly tolerant to waterlogging and yellow leaf spot disease, had good tillering capacity and maintained its juice quality over long duration[12]. Other widely adapted varieties were CP 52-68, CP 72-2086 and R 570. Exploitation of diversity at the level of varieties inadvertently led to narrow genetic base utilizing a small number of original progenitor clones and elicited interest in the genetic diversity of *Saccharum* species and related genera. At present, two world collections of sugarcane germplasm at Sugarcane Breeding Institute (SBI), Coimbatore, India (bulk collection at Cannanore) and USDA-ARS, Canal Point, USA (bulk collection at Coral Gables outside Miami, Florida); high-altitude forms of *Erianthus fulvus* and *Miscanthus nepalensis* at IARI Regional Research Station, Wellington, Nilgiri, India[13]; National Nursery for Sugarcane Germplasm Resources at Sugarcane Research Institute, Yunnan Academy of Agriculture Sciences, China, and 11 secondary germplasm collections in various countries now maintain sugarcane genetic resources. Using the hitherto untapped germplasm has proved promising as the use of Mandalaya – a *S. spontaneum* from Burma culminated in the success of Australian ‘Early CCS Canes Programme’ and use of another *S. spontaneum*, US56-15-8 led to the development of LCP 85-384, a high-yielding, high-sugar, early-ripening, less-N-requiring and cold-tolerant variety of Louisiana, which has covered a wide area[14].

Table 1. Varieties used in breeding to impart desirable traits to the progeny

Trait	Variety
Sucrose content	M 336, PR 1000, CP33-224, Co 281, PR1140
Cold resistance	CP 1165
Salt tolerance	Co 453
Drought tolerance	PR 980, Co 312
Lodging resistance	Q27
Erectness	CP38-34, CP66-346, CP52-68 (also transmits mosaic susceptibility)
Smut resistance	Co 419, Co 453, Co 603 (pistil parent)
Red rot resistance	Co 475, Co 980, Co 1227
Leaf scald	CB 38-22
Leaf scald, Red rot, Mosaic	Co 475
Leaf scald, Gumming disease, Fiji disease and Mosaic resistance	Co 290
Diatraea resistance and Red stripe susceptibility	US 1694
Wide adaptation	PoJ 2878; NCo 310

Source: Machado, Jr and Burnquist[6].

Let us now consider the diversity of the germplasm which has been and/or could be exploited for sugarcane improvement.

Diversity at the level of *Saccharum* species

Some of the *S. officinarum* clones maintain higher average cane weight (>2 kg/cane) and cane yield (>30 kg/2 m row length)[15] (Tables 3 and 4). Clones with high-sucrose content have been identified in *Saccharum* species, viz. *S. sinense:* Ikhri (17.1–18.0% sucrose); *S. robustum*: 57 NG-56, NG-74-24, NG 77-73, NG 77-59 (9.1–11% sucrose)[16]; *S. officinarum*: Creoula Rayada, 57 NG-174 (>20 % sucrose)[15]; *S. barberi*: Kansar, Lalri (17.1–18.0% sucrose)[16] and *S. spontaneum*: clones with >16.0° Brix: SES 32A, SES 65, SES 72, SES 96 B, SES 597, SES 605 (ref. 17). Besides, there are some *S. officinarum* clones which exhibit early ripening trait (Table 5). *Saccharum* species have been identified which are tolerant to abiotic and biotic stresses and have higher nutrient use efficiency (Table 6). Indigenous canes growing in India had desirable features like tolerance to drought, waterlogging, wider adaptability, ratooning, early ripening, and high yield (Table 7). Among these, Khagri grew under 6 ft water for over three months. Salt-tolerant clones have also been identified in *S. barberi:* Katha (Coimbatore), Kewali-14-G, Khatuia-124, Kuswar, Lalri, Nargori and Pathari[16], in *S. sinense*: Khakai, Panshahi, Reha, Uba – Seedling[16], and in *S. robustum:* IJ-76-422, IJ-76-470, 28 Ng 251, 57 Ng-201, 57 Ng 231, Ng 77-34, Ng 77-55, Ng 77-136, Ng 77-34, Ng 77-55, Ng 77-160, Ng 77-167, Ng 77-170, Ng 77-221 and Ng 77-237 (ref. 16).

Use of *S. spontaneum* imparts ratooning ability. At Karnal, 99 *S. spontaneum* clones had good ratooning ability when harvested in low temperatures (in winters) (B. K. Sahi, pers. commun.). Several clones of *S. officinarum*, *S. barberi*, *S. robustum* and *S. spontaneum* were introduced in breeding programmes with commercial canes at SBI, Coimbatore from 1980 onwards to produce interspecific hybrid (ISH) clones. Many of the ISH clones combined both stalk yield and juice quality traits and were on par with standards used. More than 20 ISH clones have been identified at SBI, Coimbatore having pol per cent juice of >20 at 12 months. Among these, ISH-204 had pol per cent juice of 22, while ISH-1 and ISH-3 had pol per cent juice of >21 (ref. 18). ISH-007 and ISH-135 were tolerant to water stress, waterlogging and salinity[9]. But drawbacks like formation of late tillers and spongy pith were noticed in many ISH clones. Studies at Indian Institute of Sugarcane Research (IISR), Lucknow on ISH of sugarcane (ISH lines) identified genotypes having divergent and distinct characteristics[19].

Table 2. Sugarcane varieties adapted to various abiotic stresses

Variety	Characteristics
Batjan	Vigorous growing, high tonnage, adopted to medium and poor soils
Cavengirie	Good yield on poor, dry lands
Co210	Adapted to hard, dry land and waterlogging
Co 281	Cold-resistant
C 46	Grew well in sandy 'sabana' lands and adapted to shallow lime soils
Daniel Dupont	Early ripening and adapted to high altitudes
D 109	Withstood unfavourable conditions
D 117	Withstood salt-affected soils
EK 28	Thrived fairly well on a variety of soils
POJ 36; POJ 2725	Well adapted to poor and exhausted lands
POJ 213	Adapted to a wide range of soils and withstood well wetlands and lack of drainage
POJ 2727	Adapted to dry, rocky lands
Uba	Maintained higher sucrose content and purity on alkaline soils

Source: Adapted from Earle[7].

Table 3. *Saccharum officinarum* clones with higher average cane weight

Cane weight (kg/cane)	*S. officinarum* clones
>2.5	NG 77-44; NG 77-102; IS 76-117; 28 NG 14; 51 NG 134; Kabirya; Manteiga-1585; Red Sport; Saharanpur Black
>2.0	Badila Fiji; Bandjer Masim Hitam; Caledonia Ribbon; Fiji 24; Fiji 60; Fiji 62; Mia M01; Mia V01; Mogali; Old Jamaica; Pynmana Ribbon; Preanger Stripped; Purple Mauritius; Sarawak Unknown; Saamsara; Tibbo Mird; Vae Vae Ula; Vespertina; White Cane; NC 15; 21 NG2; 21 NG 30; 21 NG 54; 28 NG 12; 28 NG 42; 28 NG 209; 57 NG 62; 57 NG 96; 57 NG 96; 57 NG 116 Striped; 57 NG 166; NG 77-104; NG 77-171; NG 77-233; IK 76-69; IK 76-70; NG 77-14; NG 77-42

Source: Sreenivasan and Nair[15].

Table 4. *S. officinarum* clones with higher cane yield

Cane yield (kg/2 m row length)	*S. officinarum* clones
>40	Keong 28NG 89, 28 NG 266, 51 NG 115G, 51 NG 156, 57 NG 116 yellow, 57 NG 136, 57 NG 244, IJ 76-36, IJ 76-420, IK 76-69, NG 77-14, NG 77-16, NG 77-42
>30	Kabirya; Kariya, Fix 29, Fix 40, Geel muntok, Manteiga-1585; Paka weli 2 SN, ULA 62, Vellai NC 5 21 NG 3, 21 NG 30, 28NG 27, 28NG 36, 28NG 72, 51 NG43, 57 NG 148, 57 NG 156, 57 NG 170, 57 NG 176, 57 NG 181, 57 NG 186, 57 NG 198, 57 NG 240, IJ 76-325, IJ 76-418, IJ 76-456, IJ 76-474, IJ 76-480, IJ 76-521, IJ 76-560, IK 76-31, IK 76-35, IS 76-214, NG 77-63, NG 77-68, NG 77-102, NG 77-127, NG 77-139, NG 77-232

Source: Sreenivasan and Nair[15].

Table 5. *Saccharum officinarum* clones exhibiting ripening trait (>20 °Brix at 210 days after planting)

°Brix	*S. officinarum* clones
>23	57 NG 161; 57 NG 174
>22	Badila; Oramboo; Otaheite; S.S. WiT; 51 NG 130; 57 NG 155; 57 NG 212
>21	Ardjoena; Azul De Casa; Boeton Licht Groen; Ceram Red; Chrystalina; Fiji B, Koelz-11131; Selemi Bali; 14 NG 241; 21 NG 30; 51 NG 121; 51 NG 123; 51 NG 124; 51 NG 125; 51 NG 127; 57 NG 166 Striped; 57 NG 226

Source: Sreenivasan and Nair[15].

Diversity at the level of genera included in *Saccharum* complex and distant hybridization

Some of the genera related to *Saccharum*, viz. *Erianthus*, *Sclerostachya* and *Narenga* constitute a closely related breeding group involved in the origin of sugarcane. Mukherjee[20] designated them as *Saccharum* complex. According to him, since all the species occurred in the Indo-Burma and China border region, this area was the centre of origin of *Saccharum* complex. Daniels and Roach[21] added *Miscanthus* sect. Diandra to the '*Saccharum*

Table 6. *Saccharum* species and related genera which may impart tolerance/resistance to abiotic stresses and nutrient use efficiency in sugarcane

Characteristics	Genera/species	Reference
Tolerance/resistance to drought	*S. spontaneum*, *Narenga* spp. *Erianthus* spp.	23, 24, 58
Tolerance/resistance to waterlogging	*S. robustum* and *S. spontaneum*	23
Tolerance/resistance to cold (performance at high altitudes)	*Miscanthus* spp., *Miscanthus nepalensis* *Erianthus fulvus* *S. spontaneum* *S. barberi*	7, 23, 25, 26, 58
Tolerance/resistance to salinity	*Erianthus* spp., *S. barberi*, *S. sinense*, *S. robustum*	16, 58
High nutrient use efficiency	*S. spontaneum* (IK 76-20, SES 24, IS 760164), *S. robustum* (51 NG 27), *S. sinense* (*Khadya*), *S. officinarum* (UB-16)	59
Low nutrient requirement	*S. spontaneum*, *Erianthus* spp.	23
Robust growth under low input conditions	*Erianthus* spp.	58

Table 7. Desirable features of indigenous canes growing in India which could be utilized in directed breeding

Variety	Tolerance to abiotic stress	Other desirable features
Subtropical India		
Chin, Chunnee, Raksi, Burra Chunnee, Baraukha	Flooding	Early ripening (harvested in December/January), high fibre, high sucrose
Agoul	Grew with less water (and manure)	
Hemja	Well adapted to early drought and late waterlogging	Heavy tillering, heavy yielder, high sucrose and purity, resistant to red rot and borers
Maneria, Chinia	Withstood waterlogging	Grew in irrigated areas, erect, high tillering, good sucrose. Maneria also tolerant to borers.
Khari	Drought and waterlogging	Good germinator, heavy yielder, good ratooner
Sewari	Flooding	Early ripening
Katha	Wide adaptability to drought, rain- fed, flooding, hot and dry climate and to a lesser extent to frost	Early ripening, thin excellent tillering
Lalri	Frost	Hardy, good tillering, also resistant to red rot
Khari, Ikhri, Khagri*	Drought and waterlogging	
Tropical India		
Kalkya, Khadya, Bansi, Sunnabile	Drought	Heavy tillering and ratooning ability
Nannal	Drought	

*Khagri grew and withstood even under 6 ft of water for over three months. Source: Sreenivasan[5].

complex' on the basis that few characters present in the complex were not present in the previous four genera. Thus, according to the present-day concept, the *Saccharum* complex has five genera: *Saccharum*, *Erianthus* Michx. sect. *Ripidium* Henrard, *Sclerostachya* (Hack.) A. Camus, *Narenga* Bor. and *Miscanthus* Anderss. sect. Diandra Keng. Among these, *Erianthus* and *Miscanthus* are presumed to be the most primitive forms[22]. Although genera such as *Erianthus*, *Sclerostachya*, *Narenga*, *Miscanthus* and *Imperata* are generally compatible with *S. officinarum*, they have been rarely used for varietal improvement[23]. C.A. Barber made the first intergeneric hybrid of *Saccharum* in 1913 at Coimbatore, when he crossed *S. officinarum* var. Vellai ($2n = 80$) with *Narenga prophyrocoma* ($2n = 30$), and found two types of hybrids ($2n = 95$ and 55).

Erianthus clones were resistant to nematodes and root parasites, had low nutrient requirements, imparted high yield with high fibre[23], and an efficient root system to tolerate drought. There are several species of *Erianthus*, a majority of which are found in the Indian subcontinent, including *E. arundinaceus*, *E. procerus*, *E. longisetosus*, *E. bengalense*, *E. ravennae*, *E. fulvus*, *E. elephantinus* and *E. hookeri*. *E. arundinaceus* represented by cane-forming types, with tremendous ability for biomass production and a high level of tolerance to biotic and abiotic stresses is considered important for exploitation in sugarcane breeding for better ratoonability, vigour, high yielding ability, tolerance to environmental stress, and resistance to diseases and pests[2]. In Barbados, hybrids derived from *E. arundinaceous* showed exceptional tolerance to drought[24], cold[25], salinity and imparted resistance to many insect pests. Additionally, when crossed with a high sugar variety there was no significant decrease in sugar content in the hybrids. Some of the *Erianthus* clones, viz. IJ76332, IJ76-365, IJ76-383, IJ76-384, IJ76-400, IK76-48, IK76-76, IK76-88, IK76-99 and IS76-199 are resistant to red rot (*Colletotrichum falcatum*, Co C 671 isolate)[26]. Brandes *et al.*[26] have also mentioned a high-yielding progeny from crosses involving *Erianthus* clone, IK64-41 in Australia. Hybrids produced by crossing Co 7201 and several clones of *Erianthus* were huge, tall with good stalk weight, °Brix and sucrose percentage and were also male fertile. Sugarcane–*Erianthus* hybrids at different stages of nobilization are under evaluation. A few clones tested at Karnal station (subtropical India) continued growth in winter; and many were resistant to red rot[27]. These characteristics make them an excellent donor for breeding high-biomass varieties with tolerance to abiotic and biotic stresses. Some promising hybrids involving sugarcane and *Erianthus* were also obtained[28]. Work on intergeneric hybridization at SBI, Coimbatore resulted in the production of several intergeneric hybrids[29]. One of the selections from Coimbatore (Co 87008) is a hybrid of Co 6304 × *Erianthus*. The hybrids involving *Saccharum* and *Erianthus* have shown great potential[30].

Narenga clones are resistant to almost all the diseases, pests and root parasites and tolerated drought, whereas *Miscanthus* clones are high-yielders, resistant to diseases and tolerant to cold. Their use in breeding could impart these characteristics to the progeny. Such crosses have been attempted in India, Fiji, Hawaii and Taiwan[23]. Downy mildew (*Peronosclerospora sacchari*) resistance genes have been successfully transferred from *Miscanthus* to sugarcane[31].

Sugarcane × sorghum hybrids ripened a little earlier under low temperature and low humidity, attained a purity coefficient of 85% or more in about 200–220 days after planting and the improvement continued for another 100 days (ref. 32). In 1938, Janaki Ammal crossed the same variety of *S. officinarum* var. Vellai with *Zea mays* to obtain first *Saccharum–Zea* hybrid with 52 chromosomes. Crossing with *Z. mays* resulted in a single hybrid, P111 which did not show earliness in ripening[33].

The distant hybridization programme of EID Parry Limited, Bangalore wherein *S. officinarum* clones were crossed with various genera indicated that hybrids with *Erianthus* showed more initial vigour and produced cane early (so was the case with *S. officinarum* × *Saccharum* spp. hybrids). Hybrids with *Sclerostachya* were tall and produced >5 m tall stalks with 30–33 internodes in 12 months. Hybrids with *Narenga* were comparatively thinner and with glabrous leaves[34].

Multiple-abiotic stress tolerance in sugarcane

Sugarcane, being a long-duration crop, experiences more than one abiotic stress which either leads to or aggravates some other abiotic and biotic stresses in the same crop cycle (Table 8) and thus multiple-stress tolerance becomes more relevant[35]. Among the indigenous canes growing in India, Hemja, Khari, Khagari and Ikri are tolerant to drought and waterlogging. Among these, Hemja is well adapted to early drought and late waterlogging, and Khagari to waterlogging. Katha is widely adaptable, tolerant to drought, flooding and to a lesser extent to frost[5]. Several sugarcane varieties exhibit multiple-abiotic stress tolerance (mainly drought/rainfed/waterlogging/salinity/low temperature)[35,36]. These include BO 34, BO 70, BO 109, BO 128, Co 210, Co 285, Co 6907, Co 86011, Co 8371, Co 87025, Co 8362, Co 87205, Co 87263, Co 87268, Co 98014, CoLk 94184, CoSi 86071, N 11, NCo 310, UCW 5465 (drought/rainfed/waterlogging), BO 106, Co 8145, Co 88019, Co 94008, Co 99004, Co 2001-13, Co 2001–15, CoM 7125, CoS 510, CoS 797, HM 645 (drought/rainfed and salt stress), BO 99, Co 395, Co 453, Co 87263 (waterlogging and salt stress), Co 312, Co 421 (drought/rainfed and low temperatures), Co 285, CoPant 90223 (drought/rainfed, waterlogging and low temperatures) and BO 90, Co 290, Co 7717, CoC 671, Co 85004, Co 87268, CoSe 96234, CoPant 97222, CoPant 93227, HM 661 (drought/rainfed, waterlogging and salt stress). Co 290, Co 86249, Co 94008 and D 109 exhibited wider adaptability against multiple-abiotic stress tolerance, whereas CoSe 96234 exhibited tolerance to all the stress conditions in general. Among many physiological and biochemical characteristics identified for tolerance to a particular abiotic stress, trehalose and betaine contents have been shown to be related to tolerance of more than one abiotic stress in sugarcane[36]. Further, more than one abiotic (or biotic) stress in the same crop cycle within the same sugarcane zone necessitates using some of these genotypes in breeding programmes along with evaluation of more number of adapted sugarcane varieties to impart multiple stress tolerance under the present-day climatic change scenario.

Candidate gene approach for 'climate-resilient' sugarcane

Current global phenomenon of climate change undoubtedly calls for 'climate-resilient' varieties to mitigate the negative influence on sugarcane production. Genomic and transcriptomic researches have led to the identification of candidate genes for abiotic and biotic stress tolerance in sugarcane. DREB (dehydration responsive transcription factor), HSP (heat shock proteins), LEA (late embryogenesis), RAB (responsive to absicisic acid), osmotin, choline oxidase and annexin[37], stress-related clusters showing differential expression (>two-fold) during biotic and abiotic stress conditions[38], sugarcane ethylene-responsive factor SodERF3 (ref. 39), upregulation of genes governing intracellular redox status[40] and

Table 8. Effect of some abiotic stresses leading to or aggravating other abiotic/biotic stresses affecting sugarcane productivity

Primary experienced stress	Leading to or aggravating abiotic stress	Leading to or aggravating biotic stress
Drought	Salinity	Wilt, smut, leaf scald, termites, shoot borer, pyrilla, mealy bugs, white flies, scale insect, mites, etc.
Waterlogging	Salinity, alkalinity, acidity, Fe toxicity, nutrient imbalance and deficiency of N, K	Red rot, wilt syndrome, pinapple disease, white fly (in ratoon crop), cut worm, scale insect and Gurdaspur borer
Low temperature	Water stress due to reduced hydraulic conductivity and *frost heaves* formation, localized partial salt stress, banded chlorosis	Stem borer in southern peninsula
High temperature	Drought	Stem borer, root borer
Salinity	Salt blight, boron toxicity	Shoot borer (*Chilo infuscatellus*)
Nutritional deficiency	–	White fly
Soil compaction	–	Early shoot borer

Source: Modified from Shrivastava and Srivastava[35].

presence of LEA (late embryogenesis abundance)-related proteins and dehydrin[41], accumulation of trehalose and proline[42,43], other stress-inducible proteins[44], early response to dehydration protein 4 (ERD4)[45] are some of the examples of genes identified in response to drought/water deficit. Similarly, for temperature and salinity stress, differential expression of genes or proteins has been unravelled. Heat stress-induced DHNs (ref. 46), genes encoding for O^-/OH^- radicals and reduction of H_2O_2 by peroxidase/catalase under heat stress[45,47,48], cold-inducible ESTs, PPDK and NADP-ME proteins and dehydrin-like proteins protecting membranes against chilling damage[49], reduced activity of sucrose phosphate synthase, NADP-MDH and pyruvate orthophosphate dikinase to maintain photosynthesis under chilling stress[50], induction of galactional synthase (GolS) and pyrroline-5-carboxylase synthetase (P5CS)[45], and osmolytes such as proline and glycine betaine[51] during salt stress are some of the examples of such differential expression under stress.

Most recently, 600 differentially expressed genes, especially those related to the transmembrane transporter activity with ~2.5-fold increase in expression of SspNIP2 (*Saccharum* homolog of a NOD26-like major intrinsic protein gene) have been identified in sugarcane after chilling stress[52]. Sugarcane transgenics overexpressing PDH45, a DEAD-box helicase gene isolated from pea, showed upregulation of DREB2-induced downstream stress-related genes and improved tolerance towards drought and salinity[53]. A sugarcane chitinase gene *ScChi* involved in host–pathogen interaction[54] and 62 differentially expressed genes having 19 TDFs (transcript derived fragments) homologous to known defence/signalling-related sequences were identified in smut and eyespot disease inoculated plants[55]. Further, differentially expressed EST clusters involved in ROS (reactive oxygen species) signalling, defence response and plant innate immunity have been identified in response to red rot infection[56]. Utilization of these specific stress-induced genes and signalling cascades may reassure the prospects of inculcating stress resistance/tolerance in elite sugarcane cultivars by their overexpression in response to a certain stress.

Concluding remarks

Biodiversity is the key to global food security[57] and so it is important not only in nature, but also in sugarcane agriculture system. In the history of sugarcane breeding, incorporation of desirable features from diverse *Saccharum* species has led to improvement of existing sugarcane varieties and sustained the ever-demanding sugar industry. However, use of limited clones of *Saccharum* species has narrowed down the genetic base and perhaps slowed down the pace of improvement in upcoming improved sugarcane varieties. Moreover, the selection process of conventional breeding results in the loss of general biological diversity; the crop is at a major risk of low genetic diversity due to intensive selection pressure. Diverse plant genetic resources provide options to plant breeders to improve the quality, diversity and performance of crops for various qualitative and quantitative attributes, resistance to abiotic and biotic stresses, besides an efficient nutrient management through development of improved varieties with desired characteristics. In this context, use of certain *S. spontaneum* clones has led to perceptible improvement of sugarcane varieties with respect to desirable agronomic traits. This has motivated scientists to look into the diversity for desirable traits not only in *Saccharum* species, but also at the level of the *Saccharum* complex comprising *Erianthus*, *Sclerostachaya*, *Narenga*, etc. The new generation ISH clones and incorporation of *Erianthus* in sugarcane breeding programmes have shown promise. Of late, identification of candidate genes for tolerance towards various biotic and abiotic stresses has opened up more avenues to impart climate resilience in elite sugarcane genotypes.

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