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RESEARCH ARTICLE

Assessment of breeding methods and parental value of Co canes developed during 1918 - 2017

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Abstract
The performance of 1454 Co canes developed during 1918 to 2017 spanning one hundred years was assessed for nine contributing characters of cane yield and juice quality to identify the best and poorest Co canes and their parentages examined to assess the relative merit of different breeding methods adopted for their development as well as the parents responsible for their development. The study identified trait specific superior and inferior Co canes as well as Co canes superior for multiple traits. All quality traits and cane yield parameters, other than number of millable canes had a preponderance of recent selections under the best group, indicating that the genetic gain achieved in a century of breeding has been substantial. The biparental crosses accounting to 89.79 % of total Co canes is the best breeding method and highlighted the importance of specific combining ability in sugarcane improvement. On the contrary, only eleven female parents and 17 male parents bred more than 50 % of the best Co canes indicated the relevance of general combining ability, thus demonstrating the importance of both additive and non-additive variances in sugarcane. A fair number of proven parents and crosses for specific traits as well as for simultaneous enhancement of multitraits were identified offering the breeder an option to choose the parental combinations guided by the per se performance as well as their breeding value. The genetic gain achieved is being sustained with the addition of novel parental clones of diverse genetic background.

Keywords: Sugarcane; Genetic improvement; Co canes; Biparental crosses; Parentage

Introduction

Until 1918, sugarcane varieties in cultivation were Saccharum species clones belonging to *Saccharum officinarum, S. barberi and S. sinense* as the source of sugar. The important commercial noble canes in cultivation were Otaheite, Cheribon and Tanna. Otaheite was the prominent cultivar in the word and was also known as Bourbon (in West Indies), Lahaina (in Java and Hawaii), Creole cane, Lousier (in Mauritius) and Vellai (in India). Cheribon was the next widespread cultivar that became the main commercial variety in many countries. Tanna, also called Caledonian cane was cultivated in Hawaii and Fiji. In sub-tropical part of the globe, the important Indian and Chinese canes which were in cultivation included Katha, Hemja, Pathri, Chin, Saretha, Laldi, Dhaul, Mungo, Matna, Chunni, Nargori, Reora, Sarauti, Baraukh, etc. (Indian canes - *S. barberi*), Uba, Cayania, Oshima, Zwinga, etc. (Chinese canes - *S. sinense*). The canes of both these species achieved commercial importance in India, China, Brazil, South Africa and the USA.

Interspecific hybridization at Java introduced the concept of nobilization (Jeswiet 1925) and the Indian work made a breakthrough with the development of the trend setter variety, Co 205 developed by crossing *S. officinarum* clone Vellai

(2n=80) with the wild and grassy S. *spontaneum* Coimbatore (2n=64) by Dr. C.A. Barber and Dr. T. S. Venkatraman. This interspecific variety was released for commercial cultivation in India during 1918 and belonged to the first batch of sixteen sugarcane varieties (Co 201 to Co 216) called 'Coimbatore canes' or 'Co canes' developed at Coimbatore. Co 205 was a huge success and served as a catalyst for breeding modern sugarcane varieties in India and abroad. Till 2019, 3188 Co canes have been developed, among which about 203 have become commercially successful and grown in large scale over years. The gene bank with all major Co canes developed till 1962 and all Co canes developed subsequently are under maintenance at ICAR-Sugarcane Breeding Institute, Coimbatore (India) (ICAR-SBI). Efficient utilization of these genetic sources rests in assessing their merits and demerits for specific traits of economic importance and the parents that contributed to their origin to prioritize the hybridization processes for a successful breeding programme in sugarcane.

Materials and Methods

The database of Coimbatore Canes (Co canes) which are improved hybrids of commercial value (Hemaprabha et al. 2017) provided the base for this study. The data on Hand Refractometer Brix at 8 months, as a measure of earliness, juice brix, sucrose per cent, juice purity, commercial cane sugar per cent (CCS%), cane diameter, cane length, single cane weight and number of millable cane (NMC) recorded at 360 days were considered to assess the efficiency of different breeding methods and parental value. The data of all the parameters were as collected in three time periods and the mean data was used to prepare the catalogue. For recent Co canes, the data from replicated trials from which the clones were promoted to Co cane status was considered so as to minimize error in their characterization. The data were statistically analysed for common statistical measures of mean, variance and standard deviation. The best and poorest Co canes for each character were identified based on mean and standard deviation and the parentages of such clones were used in order to identify the best parents and cross combinations for use in crop improvement activities and the crosses to be avoided for improving precision in breeding. The parentages of the Co canes were observed to assess the best breeding method and the best as well as poorest parents for different traits.

Results and Discussion

Coimbatore canes or Co canes have been considered as elite clones ever since their first evolution in 1918 when Dr C. A. Barber and Dr T.S.Venkatraman selected Co 205 which brought a sugar revolution in India and made interspecific hybridization the 'mantra' for varietal development in all sugarcane breeding stations of the world. The success of Co canes had far reaching results and Co canes were in cultivation in over 25 countries and appear in the pedigree of many best varieties in the world (Vision-2050 of Sugarcane Breeding Institute 2015). Since then every year ICAR-SBI has been identifying Co canes, which are the products of careful choice of parents in hybridization and rigorous selection in different stages of evaluation. For a sugarcane breeder, this pool of Co canes is a treasure house of beneficial gene pools. A proper evaluation of these clones is warranted for making genetic gain through breeding.

In this study, a comparative analysis of 1454 Co canes developed from 1918 to 2017 and under maintenance at the germplasm bank at Coimbatore for different yield and quality characters was carried out and trait specific superior and inferior Co canes were identified. The general mean, number of promising Co canes (>GM+SD) as well as undesirable canes (< GM-SD) and the

best Co canes (Mean+ 2SD) for H.R. Brix at 8 months, Brix %, sucrose %, commercial cane sugar %, cane diameter (cm), cane length (cm), single cane weight and NMC are summarized in Table 1. Grand mean for H.R. Brix (19.20 %) at 240 days was substantially high in the population as also seen for sucrose % at 360 days (18.06 %), indicating the better juice quality of Co canes and efforts in selection for improved juice quality. Cane yield parameters such as cane thickness, cane length and single cane weight recorded a mean of 2.63 cm, 204.1 cm and 1.17 kg respectively, as a reflection of the potential of these clones for cane yield realized at harvest. The best Co canes for each character (>GM+2SD) as shown in Table 1 are successful commercial canes. These clones, accounting to nearly top 2 % of the total Co canes, can serve as parents for trait specific improvement. An important observation is that all the 19 superior Co canes with high sucrose (>21.09 %) have originated since 2008 AD as a reflection of genetic advancement for the character. Similarly other juice quality traits had a preponderance of recent selections under the best group. An earlier study established progressive improvement in sucrose content of commercial releases till 2000 AD (Hemaprabha et al. 2015) and this analysis with the Co canes bred till 2017 supports genetic gain for juice quality traits being sustained in the subsequent period as well. Similarly for cane yield parameters except NMC, for which a few canes of the early period were superior, the best clones identified belonged to the last 50 years of breeding.

It is evident from the proportion of clones with extreme values that a higher proportion of superior Co canes, in relation with inferior types, could be observed for Brix, cane diameter and NMC. These primary characters are focused since the first stages of selection starting at the ground nursery and have gained through this exercise of deliberate selection. Brix and cane diameter have been subjected to more emphasis at ICAR-SBI and seedlings with Brix below 18 per cent are generally rejected. Similarly, based on a philosophy of 'thick cane breeding' in vogue for tropical India since early days, an otherwise promising clone with less than 2.5 cm in diameter is less likely selected under the elite group of Co canes. Though studies on heritability of traits differed greatly among experiments (Balasundaram and Bhagyalakshmi 1978; Nair et al. 1980; Jackson 1994; Bakshi Ram 2005; Abu-Ellail et al. 2018), Brix is reported to have medium to high heritability and hence has been a reliable trait in selection. Also selection for important characters with low heritability has been effective in improving the population despite low efficiency for individual clones (Skinner 1986).

The method of breeding followed and the parentage of every elite selection are examined by a breeder in the pursuit for selecting the best parents for a successful breeding work. The breeding methods generally practiced are biparental mating, polycrosses and general collection from the designated female parents. Selfing has also been practiced as a breeding method mainly for jucie quality based on the classic study by Stevenson (1965). Non-conventional methods of selection based on somaclonal variations and mutation breeding were also practiced at ICAR- SBI following the first reports of successful production of somaclones in 1979 (Sreenivasan and Jalaja 1979) and induced mutations in 1959 (Panje and Jagadesan 1959). The immediate parentage of 1454 Co canes showed that the vast majority of Co canes, numbering 1240 were bred through biparental mating, while 82 Co canes were developed from general collections (GC), 32 from polycrosses, five through selfing, apart from 15 somaclones and seven mutants (rest have anonymous parentage). The biparental crosses accounted to 89.79 % of total Co canes and undoubtedly emerged as the best breeding method. Biparental crossing is done through

Table 1. Character-wise performance of Co canes showing the general mean and the number of desirable and undesirable Co canes

Character	Mean	SD	No. of Co canes >M+SD	No. of Co canes <M-SD	Best Co canes (>GM+2SD)
Earliness (H.R. Brix @ 8 months)	19.20	1.51	215	219	Co 11015, Co 17008, Co 15007, Co 14025, Co 14007, Co 16001, Co 14002, Co 17005, Co 15014, Co 12025, Co 09007, Co 13016, Co 08016, Co 16002, Co 09015, Co 16007 (>22.22 %)
Brix %	20.11	1.75	248	234	Co 15017, Co 14011, Co 12025, Co 14025, Co 11015, Co 14027, Co 91019, Co 17005, Co 16001, Co 11021, Co 85001, Co 14007, Co 16002, Co 94012, Co 8367, Co 89025, Co 87265, Co 87007, Co 15008, Co 14010, Co 16005, Co 14030, Co 14016, Co 17003 (>23.61)
Sucrose % @ 360 days	18.06	1.87	222	243	Co 11015, Co 89025, Co 14007, Co 15017, Co 17005, Co 12025, Co 15007, Co 17003, Co 87265, Co 94012, Co 15008, Co 89023, Co 96002, Co 14030, Co 09004, Co 14016, Co 10005, Co 17008, Co 88006, Co 13009, Co 13020 (>21.09)
CCS %	12.51	1.43	231	235	Co 89025, Co 15007, Co 17005, Co 12025, Co 17003, Co 87265, Co 15017, Co 89023, Co 96002, Co 94012, Co 15008, Co 88006, Co 13009, Co 13020, Co 15014, Co 17008, Co 10005, Co 11015, Co 14007 (>15.37)
Cane diameter (cm)	2.63	0.35	243	229	Co 0208, Co 87009, Co 2000-08, Co 8369, Co 10021, Co 10020, Co 62146, Co 62175, Co 7312, Co 97014, Co 11007, Co 86034, Co 10019, Co 7706, Co 17008, Co 07005, Co 0305, Co 98004, Co 88029, Co 98010, Co 95007, Co 87002, Co 0203 (>3.34 cm)
Cane length (cm)	204.1	36.45	213	253	Co 93013, Co 10018, Co 16018, Co 10022, Co 16006, Co 0222, Co 10017, Co 99009, Co 10010, Co 16017, Co 0114, Co 93004, Co 16009, Co 99007, Co 86006, Co 98014, Co 10020, Co 87016, Co 94005, Co 16027, Co 16013 (>277.04 cm)
Single cane weight (Kg)	1.17	0.369	213	254	Co 88025, Co 8353, Co 16020, Co 16018, Co 16023, Co 0325, Co 86034, Co 93004, Co 8368, Co 86041, Co 8355, Co 7636, Co 7647, Co 7717, Co 7806, Co 90005, Co 94008, Co 98005, Co 98003, Co 8365, Co 16026, Co 16011 (>1.90 Kg)
NMC (‘000/ha)	103.56	27.51	273	238	Co 88015, Co 7220, Co 92016, Co 7812. Co 8227, Co 8228, Co 0312, Co 7302, Co 8337, Co 7225, Co 62260, Co 89016, Co 88036, Co 88029, Co 07004, Co 1095, Co 7910 (>158.57)

careful choice of two parents guided by their *per se* performance, complementarity of characters and specific combining ability (SCA) and genetic diversity measured based on pedigree, biometrical or molecular methods, while other breeding methods are based on general combining ability (GCA). The large proportion of Co canes emanating from biparental mating gives ample evidence of the importance of specific combining ability as well as genetic diversity of the parental combinations to be considered while choosing parents. The number of different biparental crosses was also very large (620), in relation to 43 general collections and 23 polycrosses respectively. While proving the advantage of biparental mating, this result shows the importance of scientific choice of the best possible parental clones and cross combinations to harness the best out of the genetic divergence available in the breeding pool.

It could be seen that 25 crosses alone accounted to 25 % of the Co canes. The crosses Co 312 x Co 285 and Co 458 x Co 658 of the early period (till 1960), Co 740 x 775, Co 7201 x Co 775, Co 740 x Co 6806 of the middle period (until 1995) and Co 8371 x Co 86011 and Co 86032 x Co 86011 of the latest period (until 2016) were the most successful cross combinations over the years. These time-tested cross combinations also accounted to the development of commercially popular Co canes over years.

The immediate parents of 1454 Co canes were 182 female and 245 male parents. The parents and the number of Co canes emanating from these as given in the parenthesis were Co 7201 (93), Co 312 (78), CoC 671 (78), Co 740 (69), Co 419 (64), Co 8371 (46), Co 6806 (41), Co 449 (34), Co 775 (30) and Co 86002 (27). These parents contributed to the development of 48.1% of Co canes, while from ten male parents viz. Co 775 (125), Co 6806 (64), Co 86011 (64), CoC 671 (51), Co 1148 (38), Co 658 (33), CoT 8201 (33), Co 285 (33), Co 62174 (29) and Co 453 (27) 36 % of Co canes were developed. Though it has been a practice to use large number of parents based on *per se* performance, this finding of successful parents is significant and emphasises the importance of combining ability in sugarcane breeding. Line x tester analysis has been used to evaluate

Table 2. Parents of superior and inferior Co canes and the most common parents

Parents of superior and inferior Co canes		Number of parents generated high frequency of Co canes		
		Total	More than one Co cane	Parents generated of ≥ 50% Co canes
Parents of 268 superior Co canes	Female	82	29	CoC 671, Co 7201, Co 8371, Co 86032, Co 86002, Co 7704, Co 86011, CoC 90063, Co 85002, Co 7314, Co 99006 (11 parents)
	Male	85	27	Co 86011, Co 775, CoC 671, Co 94008, Co 88013, Co 6806, Co 7717, Co 05001, Co 1148, Co 62198, Co 85002, Co 0218, Co 7314, Co 62174, Co 94019, MS 6847, IG 91-1100, Co 86249 (18 parents)
Parents of 363 inferior Co canes	Female	105	45	Co 312, Co 449, Co 740, Co 421, Co 419, Co 1148, Co 1158, CoS 109, Co 6806, Co 7201 (10 parents)
	Male	94	45	Co 285, Co 453, Co 775, Co 6806, Co 1148, CoL 9, Co 617, Co 1287, Co 312, Co 658, BO 10, BO 17, CoC 671 (13 parents)

parents for their general and specific combining ability by Bhagyalakshmi et al. (1986) and Ram and Hemaprabha (2000) who observed higher contribution of line x tester for Brix and sucrose %, respectively. In experiments with diallel crosses, SCA was greater than GCA for both cane yield and sugar content (Rao and Ethirajan 1983). Several studies on combining ability have been performed with limited numbers of parents. This study is a clear demonstration of the successful parental clones with high general combining ability. Therefore, combining the observations on the success of biparental crosses and the efficiency of selected Co canes as proven parents, and it can be inferred that both additive and non-additive variances are equally important in sugarcane. Hence parental choice has to be based on *per se* performance of the Co canes as well information on their combining abilities

Considering all the nine characters together, those Co canes surpassing the general mean (GM+SD) and those falling below mean (Mean-SD) for more than seven characters were identified as the best and the poorest Co canes respectively. Accordingly, there were 268 superior Co canes for multitraits and the best material identified through this study. At the same time, 363 inferior Co canes identified might not have any more relevance in

Table 3. The best cross combinations generating a higher frequency of selections for eight characters

Character	Best Cross combinations
NMC	Co 7201 x Co 775, Co 62198 x CoC 671, Co 312 x Co 285, CoC 671 x Co 6806, Co 740 x Co 6806, CoC 671 x CoT 8201, Co 740 x Co 6304, Co 740 x Co 62174, Co 7314 x Co 775, Co 449 x Co 658, Co 6304 x Co 775
Single cane weight	Co 8371 x Co 86011, Co 419 x CoC 671, Co 6304 x CoC 671, Co 7201 x Co 775, Co 7704 x CoC 671, Co 98010 x Co 94008, Co 62198 x CoC 671, Co 7314 x Co 775, Co 740 x Co 775, Co 740 x Co 7409, CoC 671 x IG 91-1100, CoC 90063 x Co 88013
Cane diameter	Co 419 x CoC 671, Co 419 x Co 775, Co 419 x Co 6806, Co 6304 x Co 775, Co 7201 x Co 775, Co 740 x Co 775, Co 740 x Co 6806, Co 7704 x CoC 671, Co 8371 x Co 86011, Co 8371 x Co 85002, CoC 671 x IG 91-1100, CoC 90063 x Co 88013, Co 86002 x Co 775, Co 88002 x Co 62174
Cane length	Co 740 x Co 775, Co 8371 x Co 86011, Co 62198 x CoC 671, Co 7201 x Co 775, Co 86032 x Co 86011, Co 419 x Co 6806, Co 98010 x Co 94008, Co 99006 x Co 94008, Co 86032 x Co 05001, Co 86032 x Co 94008
HR Brix @ 240 days	Co 8371 x Co 86011, Co 86032 x Co 86011, Co 86032 x Co 05001, Co 7201 x Co 775, Co 85002 x Co 86011, Co 86002 x Co 775, Co 86011 x CoT 8201, Co 88002 x Co 62174, CoC 671 x CoT 8201, CoC 671 x Co 6806
Brix	Co 8371 x Co 86011, Co 86032 x Co 86011, Co 86032 x Co 05001, Co 7201 x Co 775, Co 85002 x Co 86011, Co 86002 x Co 775, Co 86011 x CoT 8201, Co 88002 x Co 62174, CoC 671 x CoT 8201, CoC 671 x Co 6806
Sucrose	Co 8371 x Co 86011, Co 86032 x Co 86011, Co 8371 x Co 85002, Co 86002 x Co 775, Co 86032 x Co 05001, Co 86011 x CoT 8201, Co 85002 x Co 86011, Co 85002 x OH 44
CCS %	Co 86032 x Co 86011, Co 86002 x Co 775, Co 8371x Co 86011, Co 8371 x Co 85002, Co 86011 x CoT 8201, Co 86032 x Co 05001, CoC 671 x CoT 8201, CoC 90063 x Co 88013, Co 85002 x Co 86011, Co 85002 x OH 44

breeding. Dealing specifically with the parents of such Co canes that generated better and poorer Co canes, it was found that 50 per cent of the Co canes were derived from a few parents (Table 2). For instance, though 82 female parents were involved in the development of 268 superior Co canes, only 11 parents generated more than 50 per cent Co canes. While 29 parents generated two or more Co canes, the rest (53) produced one Co cane each. Similarly, 18 out of 85 male parents produced 50 per cent of the best Co canes. From Table 2, it could be inferred that the number of parents that produced inferior Co canes were more than those of the superior Co canes. This finding again stresses the need for careful choice of parents. The best parents as listed in Table 2 have demonstrated their ability as general combiners and may be tried with recent commercial types and genetic stocks for advancing genetic gain.

The best cross combinations responsible for generating the superior Co cane were identified as presented in Table 3. In all, 22 crosses were advantageous for two or more characters. The cross Co 8371 x Co 86011 was on top that yielded superior Co canes for six characters (single cane weight, cane diameter, cane length, HR Brix at 8 months, Brix and sucrose %), two crosses viz. Co 86032 x Co 86011 and Co 86032 x Co 05001 were better for five traits (cane length, H..R. Brix at 8 months, Brix, sucrose % and CCS%), three crosses (CoC 671 x CoT 8201, Co 86002 x Co 775, Co 86011 x CoT 8201) were better for four characters and the remaining 16 crosses were beneficial for two to three characters. These crosses are good specific combiners of proven cross status for effecting hybridization and raising seedlings in large numbers. Two crosses CoC 671 x IG 91-1100 (for single cane weight and cane diameter) and Co 85002 x OH 44 (for sucrose % and CCS%) need special mention as these are novel combinations involving two elite products emerged through pre-breeding activities involving *Erianthus arundinaceus* and Keong (*S. officinarum*) respectively.

Conclusion

This analysis gave a clear picture on the merit of biparental crossing and a breeder has good option of choosing the parental combinations guided by the results of a century of breeding research. It is encouraging to learn that recent crosses are more productive to yield superior Co canes for multitraits and that genetic gains achieved over the period is substantial. About two per cent of the Co canes are superior to different traits and may be used for targeted trait enhancement programmes. This exercise also identified a fair number of proven parents and crosses for specific traits as well for simultaneous enhancement of multitraits. The inferior Co canes may be avoided in crossing. Such clones may be genetically inferior or might have degenerated over years. Evaluation of the rejuvenated clones would test their genetic potential to decide maintenance of such clones in the commercial pool. It is a fact that one hundred years of breeding has given rise to several spectacular varieties over time making use of the available genetic variability, which is also enhanced with the addition of genetically improved clones as well as with novel new genetic base as parental clones. This study could identify two such parents OH 44 and IG 91-1100 which are interspecific and intergeneric hybrids respectively with a genetic base not so far represented in the commercial gene pool.

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