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Genetic Improvement of Sugarcane (*Saccharum* spp.) Contributed to High Sucrose Content in China Based on an Analysis of Newly Developed Varieties

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Abstract: In China, sugarcane (*Saccharum* spp.) hybrid cross-breeding began in 1953; approximately 70 years since then, >100 commercial sugarcane varieties have been created. In this study, 88 commercial varieties bred in China between 1953 and 2010 and 12 original foundational varieties were planted to investigate the effect of improving sugarcane varieties in China. Considering 20 years as a time node, the commercial varieties were classified into four improved generations. Retrospective analysis showed significant improvements in sucrose and other technological characteristics of commercial sugarcane varieties. The adoption of improved varieties over generations has continuously increased sugarcane's sucrose, juice sugar, and gravity purity, and the difference was significant between Gen1 and Gen3, and between Gen2 and Gen4. Gen4 showed 2.06%, 2.35%, and 3.69% higher sugarcane sucrose ($p < 0.01$), juice sugar ($p < 0.01$), and purity ($p < 0.05$), respectively, and 1.13% lower sugarcane fiber ($p < 0.01$) than Gen1, the original foundational hybrid varieties. The development of new varieties has improved the technological characteristics of Chinese sugarcane. Sugarcane sucrose, juice sugar, and purity showed an increasing trend. Sugarcane fiber content did not significantly change with the development of new varieties but declined in comparison with the original foundational hybrid varieties.

Keywords: sugarcane (*Saccharum* spp.); variety; sucrose; technological characteristics; improvement generations

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1. Introduction

Sugarcane (*Saccharum* spp.) is a gramineous C_4 plant and is an important raw material for sugar production worldwide. At the same time, because of its strong photosynthetic capacity, high biological yield, and total fermentable sugar, sugarcane has shown good advantages and development prospects for utilization as an energy material [1]. Sugarcane has ideal biological and botanical characteristics for the production of fuel ethanol and it can significantly reduce the greenhouse effect [2]. Sugarcane has been planted in China for more than 2000 years, but hybrid cross-breeding of sugarcane began only in 1953 with the establishment of the Hainan Sugarcane Breeding Farm [3]. At present, the main sugarcane-producing areas in China are concentrated in Guangxi, Yunnan, Guangdong, and Hainan. In 2020, the total sugarcane planting area in China was approximately 1.35 million hectares, with approximately 0.8 and 0.3 million hectares in Guangxi and Yunnan Provinces, respectively. As of 2020, China has bred and approved more than 300 commercial sugarcane varieties [4,5], and more than 100 varieties were planted in the production areas. The chief cultivated varieties in production belong to the Guitang (GT), Yuetang (YT), Yunzhe (YZ), Funong (FN), Liucheng (LC), and Taiwan (ROC) series. After decades of developing new varieties, the agricultural economy and technological infrastructure have improved rapidly, and China's sugarcane industry and variety structure have undergone profound changes. Early varieties such as Huanan (HN), Chuantang (CT), Ganzhe (GZ), and Mintang (MT) have gradually disappeared, and the corresponding breeding practices no longer exist. With continuous improvement and development, sugarcane varieties continue to be replaced and updated; some varieties have been eliminated, and new superior varieties are being planted. However, it cannot be denied that these varieties have had a profound and enduring impact on the development of the sugarcane industry and the breeding of new varieties, and most of these varieties are still the main parents of modern cross-bred varieties of sugarcane in China.

The main product of sugarcane is sugar, and the sugar yield depends on the sugarcane's yield and sucrose content; thus, the general goal of sugarcane breeding to achieve a high yield and high sucrose content so as to obtain the highest sugar yield. Earlier research [6] reported that according to the statistics of the United States Department of Agriculture (USDA), from 1959 to 2021, the global sugar output increased from 57.212 million tons to 185.537 million tons, of which the sugar cane increased from 38.579 million tons to 146.788 million tons. The countries with the greatest sugarcane yield per unit of area are India (70.61 t/hm^2), Mexico (69.87 t/hm^2), China (69.51 t/hm^2), South Africa (66.92 t/hm^2), Thailand (66.17 t/hm^2), Brazil (61.67 t/hm^2), the Philippines (58.81 t/hm^2), Pakistan (56.76 t/hm^2), and Cuba (38.53 t/hm^2). The sugar yield of sugarcane in different countries, ranked from high to low, is 12.13% for Brazil, 11.83% for Mexico, 11.83% for China, 11.37% for South Africa, 10.43% for Thailand, 10.01% for Cuba, 9.97% for Pakistan, 9.75%for the Philippines, and 9.50% for India. According to the statistics of the International Society of Sugar Cane Technicians (ISSCT), the scientific and technological contribution rate of improvements in sugarcane varieties is as high as 60% [7]. However, high-yield varieties generally have a low sucrose content, and varieties with a high sucrose content generally have low yield. Obtaining the ideal sugarcane variety with a high yield and a high sugar content is relatively difficult. Research has reported that comparisons of cultivars released in different years have indicated that sugarcane breeding programs have achieved increased sugar yields via improvements in cane yield, with a considerably smaller contribution of increased sugar content [8], contrary to what might be expected. However, for energy sugarcane, the goal of hybrid breeding is to obtain the highest yield of total fermentable sugars (sucrose, glucose, and fructose) per unit of area. The goals of breeding new varieties are high biological yield, a high total sugar content, a high fiber content, strong resistance, and adaptability [9].

Sugarcane is an allopolyploid plant with complex heredity, a large number of chromosomes, and a complex genetic linkage map [10]. Therefore, achieving genetic regularity and selecting the combinations of hybrid parents is challenging. At present, major sugarcane-growing countries in the world have their own breeding systems that mainly focus on the sugar yield. For example, the United States has adopted the method of recurrent selection [11], that is, selecting the best progeny as parents and then crossing them further with varieties with other desirable characteristics to obtain offspring with superior characteristics. Chinese sugarcane breeders prefer to select a hybrid combination that has repeatedly produced varieties with superior characteristics to the combination, or at least varieties with the same excellent characteristics can be selected [12]. This is contrary to the American recurrent selection theory but is similar to the Australian breeding method, in which excellent hybrid combinations are used for repeated hybridization [13].

Since the establishment of sugarcane hybrid cross-breeding in China, the sugarcane breeding program in all provinces and regions of mainland China have adopted the "five nurseries" system [14]. Within this breeding procedure, the cultivation of an improved sugarcane variety generally requires 8–10 years: the hybrid nursery in the first year, the seed selection nursery in the second year, the identification nursery in the third year, preparation for the comparison test in the fourth and fifth years, a product comparison test in the fifth and sixth years, a regional test in the sixth to eighth years, demonstration and of the improved varieties in the eighth to tenth years [15]. Therefore, the promotion of a good variety occupies a certain area of production for at least 10 years. In this study, we collected and planted the main commercial sugarcane varieties bred by various breeding institutions since the establishment of the sugarcane cross-breeding program in 1953 until 2010, and the 12 early interspecific hybrids varieties of sugarcane including the POJ series, CO series, and others, which are the core parents for global sugarcane hybrid breeding [16]. According to sugarcane breeding procedures and the development regulations and reality of the Chinese sugarcane industry, these varieties were divided into four improved generations. From the perspective of populations, this study investigated the changes in the main technological quality characteristics in different improvement periods and analyzed their development across the different improved generations in China. The technological characteristics of sugarcane are mainly affected by genotype inheritance, and previous research [17] has reported that the yield has increased significantly in China. We mainly analyzed the changes in sugarcane's technological characteristics in this study through a retrospective analysis of variety development to provide a reference for the hybridization and innovative utilization of the sugarcane germplasm in China.

2. Materials and Methods

2.1. Experimental Materials

In total, 100 sugarcane varieties were tested, including 88 commercial varieties bred in China between 1953 and 2010, and 12 early interspecific hybrids varieties of sugarcane (Table 1). The varieties included 27 of the "Yunzhe" series (referred to as "YZ"), 3 of the "Chuantang" series (referred to as "CT"), 3 of the "Dezhe" series (referred to as "DZ"), 3 of the "Funong" series (referred to as "FN"), 15 of the "Ganzhe" and "Gannan" series (referred to as "GZ/GN"), 2 of the "Huanan" series (referred to as "HN"), 4 of the "Liucheng series (referred to as "LC")", 4 of the "Mintang" series (referred to as "MT"), 11 of the "Yuetang" and "Yuegan" series (referred to as "YT/YG"), and 16 of the "Guitnag" series (referred to as "GT"). The original foundational hybrid varieties included the POJ series, the CO series, Kassoer, and EK28, which were the core parents of early hybrid varieties of sugarcane.

2.2. Experimental Design

In total, 100 sugarcane test varieties were planted to study the differences in the main technological characteristics (sugarcane sucrose, juice sugar, fiber, and purity). Considering 20 years as a time node, the 100 sugarcane varieties were divided into four improved generations, mainly on the basis of the progress in sugarcane cross-breeding and the process of commercial variety breeding in China. The first improved generation (hereafter referred to as Generation1) included the 12 original foundational hybrid varieties including the POJ series, the CO series, Kassoer, and EK28. The second, third, and fourth improved generations (hereafter referred to as Generation 2, Generation 3, and Generation 4) included commercial varieties bred in 1953 to 1970, 1971 to 1990, and 1991 to 2010, respectively. Detailed information on the 100 variety resources and their parents is provided in Table 1.

2.3. Field Planting Method and Experimental Site

A field experiment was set up on 20 December 2016 and finished in March 2020. We kept the first ratoon (April 2018–March 2019) and second ratoon (April 2019–March 2020) of the sugarcane and formed three crops. We collected data on the characteristics of 3 crops including the planted cane (2017–2018), the first ratoon (2018–2019), and the second ratoon (2019–2020). The test soil type is clay. A randomized complete block design was applied in our experiment with two replications. The 100 varieties were evaluated, and each variety was planted in rows with a length of 8.0 m, and a row spacing of 1.1 m. Each variety was planted in 10 rows, with protective rows that occupied an 88 m^2 plot area of each replication. This part was determined as previously reported [18]. In the planted cane (December 2016–March 2018), we cut the sugarcane stalks into several billets with 3 buds or 4 buds, planted the billets, and sprinkled fertilizer into the furrow at a depth of 40 cm then covered them with 15 cm of soil. Sugarcanes were planted at a density of 8000 buds/mu, and a compound fertilizer ($N{:}P_2O_5{:}K_2O$, 18:7:20) was used at 80 kg/mu.

2.4. Climate Conditions of the Experimental Site

The location was in the Sugarcane Research Institute, Yunnan Academy of Agricultural Sciences (Kaiyuan City, Yunnan Province; 23.7° N, 103.25° E) at an altitude of 1051.8 m. It has a subtropical plateau monsoon climate, with sufficient light resources. See Table 2 for the detailed climatic parameters, reproduced or adapted from *Agronomy*, 2022 [18].

Table 1. Sugarcane test variety resources, their parents, and their classification into the four improved generations.

Number	Generation	Variety	Female	Male	Number	Generation	Variety	Female	Male
1	1	POJ213	Black Cheribon	Chunnee	51	4	DZ93102	GT73167	YC73512
2	1	POJ2725	POJ2364	EK28	52	4	DZ9388	YC71347	CP721210
3	1	POJ2836	POJ2364	EK28	53	4	FN30	CP841198	ROC10
4	1	POJ2878	POJ2364	EK28	54	4	FN38	YT83257	YT83271
5	1	CO1001	CO270	CO743	55	4	FN39	YT91976	CP841198
6	1	CO281	POJ213	Co206	56	4	GN0021	CP57614	YC84125
7	1	CO290	Co221	D74	57	4	GN008	CP57614	YC84125
8	1	CO285	Mauritius	Spont.co.	58	4	GN01112	GZ7565	CP5761
9	1	CO419	POJ2878	CO290	59	4	GZ02302	GZ14	CP57614
10	1	CO421	POJ2878	Co285	60	4	GN912	CP76380	CP78304
11	1	Kassoer	Black Cheribon	Black Cheribon	61	4	GT30	YT30	ROC1
12	1	EK28	EK2	POJ100	62	4	GT31	YT85177	CP811254
13	2	CT57416	Co281	F134	63	4	GT35	GT69156	ROC22
14	2	GT60149	CO290	CP4950	64	4	GT94119	GZ7565	YC71374
15	2	GT60289	F134	CP4950	65	4	GT96211	Pindar	GT96167
16	2	GT69156	HN5612	CO331	66	4	GT27	YT851622	YC84125
17	2	GT69360	HN5612	CP49-50	67	4	GZ0270	GT69435	CP841198
18	2	GZ64137	NCo310	YC6270	68	4	GZ95108	ROC1	YC71374
19	2	GN65347	CP34120	F134	69	4	LC031137	HOCP93746	ROC22
20	2	HN5411	F108	F134	70	4	LC03182	CP721210	ROC22
21	2	HN5612	F108	F134	71	4	LC05136	CP811254	ROC22
22	2	MT69421	CP33310	F134	72	4	LC07150	YT85177	ROC22
23	2	MT70611	CP4950	F134	73	4	MT99596	Co1001	YC73226
24	2	YZ6424	CO419	POJ2878	74	4	MT92505	C01001	CP731547
25	2	YZ65225	Co419	F108	75	4	YG43	YT93213	YT93159
26	2	YZ68154	Co419	CP4950	76	4	YT00236	YN73204	CP721210
27	3	CT7915	CT61380	NJ58321	77	4	YT00318	YN73204	CP861633
28	3	CT89103	CP34120	YC71374	78	4	YT79177	HN5612	YC73226
29	3	GN79216	NCO310	CP44101	79	4	YT93159	YN73204	CP721210
30	3	GN81711	CP67412	YC6270	80	4	YT94128	ZZ80101	ROC1
31	3	GN82660	NCO310	YC37512	81	4	YT9686	YT85177	ZZ74141
32	3	GN89131	GZ82660	CP721210	82	4	YZ011413	YT85177	ROC10
33	3	GT11	CP4950	CO419	83	4	YZ022332	CP70321	ROC10
34	3	GT12	CO419	CZ57416	84	4	YZ022540	ROC11	CP723591
35	3	GT715	YT59264	HN5612	85	4	YZ02588	CP721210	YT843
36	3	GT84332	HN5612	NJ59782	86	4	YZ05226	ZZ74147	CP721210
37	3	GT86267	YT5965	YC72399	87	4	YZ0549	YC9056	ROC23
38	3	GT895	GT73167	YC6240	88	4	YZ06407	YT9720	ROC5
39	3	GZ7565	GZ64137	NJ57416	89	4	YZ0680	ROC5	CP723951
40	3	GZ76567	GN65542	NJ57416	90	4	YZ081095	CP841198	Ke5
41	3	YT843	CO419	CP57614	91	4	YZ081609	Yz94343	Yt00236
42	3	YT85177	YT57423	CP57614	92	4	YZ082060	YT93159	Q121
43	3	YT85633	YT595	CP57614	93	4	YZ091028	YR05178	MT862121
44	3	YT89240	CP721210	GT73167	94	4	YZ091601	CP941100	CT89103
45	3	YZ71388	YZ65225	YC59818	95	4	YZ102698	ROC22	GT9266
46	3	YZ7195	YC5863	CP4950	96	4	YZ103148	YT93159	ROC22
47	3	YZ89151	GZ64137	NJ57416	97	4	YZ91510	CP4950	GT69435
48	3	YZ89351	YC8296	GT11	98	4	YZ9219	GZ64137	CP67412
49	3	YZ897	XUAN15	YC84125	99	4	YZ94375	CP721210	YC73512
50	4	DZ0383	YT85177	ROC22	100	4	YZ9991	ROC10	YC84125

Table 2. Climate data in different years.

Years	Sunshine (h)	Average Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)	Average Rainfall (mm)	Potential Evaporation (mm)	Frost-Free Period (day)
2017	1960	20.1	34.1	3.3	1038.4	1987	341
2018	2125.3	21.5	37.7	0.2	698.2	1880	320
2019	2033.7	20.8	36.2	4.2	592	1860	330

2.5. Data Collection

The industrial characteristics of sugarcane include sucrose content, the sugar content of the juice, fiber content, and purity. These were determined with reference to a previous report [19]. Juice was extracted from three stalks selected randomly from every replicate using a mechanical cane juicer in all environments. The extracted juice was examined for sucrose content (%), sugar content of the juice (%), and purity (%) using an automatic saccharimeter (Autopol 880, Rudolph Research Analytical, Hackettstown, NJ, USA). For this, we took 100 mL of sugarcane juice, used a straw to suck one drop onto the prism of a J257 refractometer to measure and observe the Brix, and read the temperature of sugarcane juice. We added an appropriate amount of basic lead acetate to shake up and filter the rest, and used a 200 mm observation tube to measure the direct optical rotation reading on the Autopol 880 polarimeter. Determination of the dry weight of bagasse was carried out as follows. We weighed 100 g of fresh bagasse for each sample, placed it in a stainless steel dish, placed this into an electric blast drying oven, baked it at 105 °C for 3.5 h, and weighed the bagasse to determine the fiber content (%). Planted canes were sampled monthly from November 2017 to March 2018, the first ratoon was sampled monthly from November 2018 to March 2019, and the second ratoon was tested monthly from December 2019 to March 2020.

2.6. Data Analysis

Microsoft Excel 2019 (Microsoft, Redmond, WA, USA) was used for collecting and sorting the data. Multiple comparisons were analyzed for different traits and different generations by an LSD (post hoc) test by DPS v14.10 software (Zhejiang University, Hangzhou, China). R software (version 4.1.0, R core team, 2021) [20] was used for creating the figures. The software package "ggplot2" was used to draw the line charts and box diagrams, the package "ggsignif" was used for the LSD test, and the packages "ggpubr" and "ggpmisc" were used for linear regression analysis. Detailed programming codes can be found at the "The R Graph Gallery" webpage [21].

3. Results

3.1. Variance in the Technological Characteristics among 100 Varieties

The sucrose content, sugar content of the juice, fiber content, and purity of the planted cane, first ratoon, and second ratoon differed significantly ($p < 0.01$) among the sugarcane varieties, and the coefficient of variation was 3.89–12.86% (Table 3).

Table 3. Analysis of variance of four technological traits in 100 sugarcane varieties.

Traits	New Plantation (%)			Ratoon 1 (%)			Ratoon 2 (%)		
	Mean	CV	SD	Mean	CV	SD	Mean	CV	SD
Sugar content of the juice	17.82 **	11.28	4.04	18.52 **	8.94	2.74	19.39 **	8.84	2.93
Sucrose content of the cane	14.52 **	10.72	2.42	14.78 **	8.69	1.65	15.44 **	8.45	1.70
Purity	86.62 **	4.65	16.25	84.43 **	5.13	18.76	85.97 **	3.89	11.21
Fiber content	13.34 **	12.86	2.94	15.08 **	12.47	3.53	15.25 **	12.61	3.70

** $p < 0.01$ according to the LSD test. CV, coefficient of variation; SD, standard deviation.

3.2. Analysis of Improvements in the Sugar Content of Juice

The sugar content of sugarcane juice showed an increasing trend with the development of improved generations in different months, and a similar trend was observed in the planted cane, first ratoon, and second ratoon cane crops, and the average over the three crops (Figure 1).

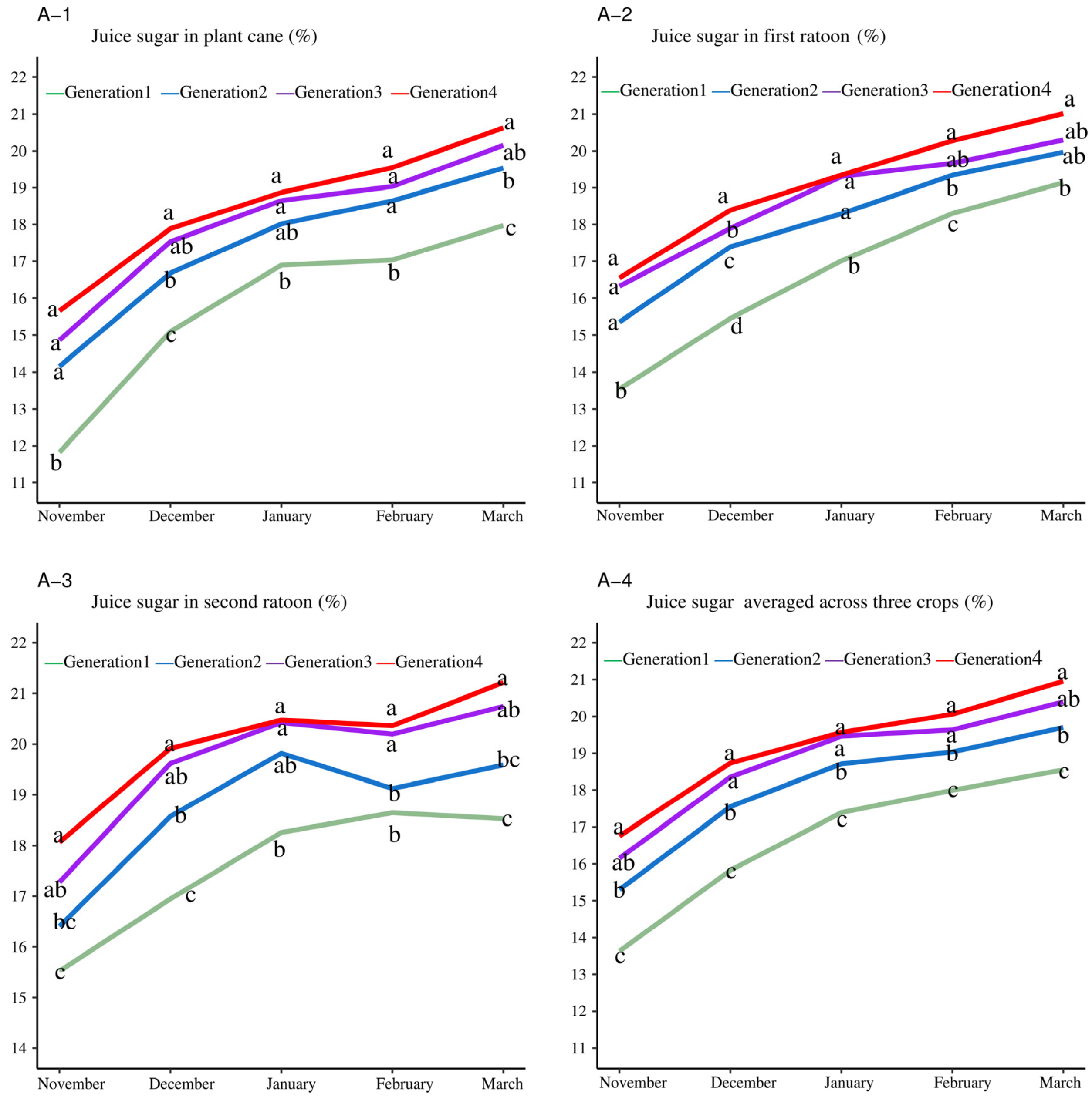

Figure 1. Analysis of the improvement in the sugar content of juice in four generations of sugarcane varieties in China. Monthly differences (November to March) of the four generations of planted cane (**A-1**), the first ratoon (**A-2**), the second ratoon (**A-3**), and the average content across three crops (**A-4**). a, b, c, d, $p < 0.05$, determined by the LSD test; the LSD test was across generations within a month.

3.3. Analysis of Improvements in Sugarcane Fiber

Sugarcane fiber content among different generations showed different growth trends in different months and different crops. With the growth of sugarcane, the sugarcane fiber content increased continuously, and the rate of the increase in sugarcane fiber differed among the four generations (Figure 2). The fiber content in Generation 1 was the highest and increased at a faster rate over 5 months, whereas the fiber content in Generation 2 was the lowest. The variation in fiber content among the generations was consistent in the planted cane, the first ratoon, the second ratoon, and across all three crops.

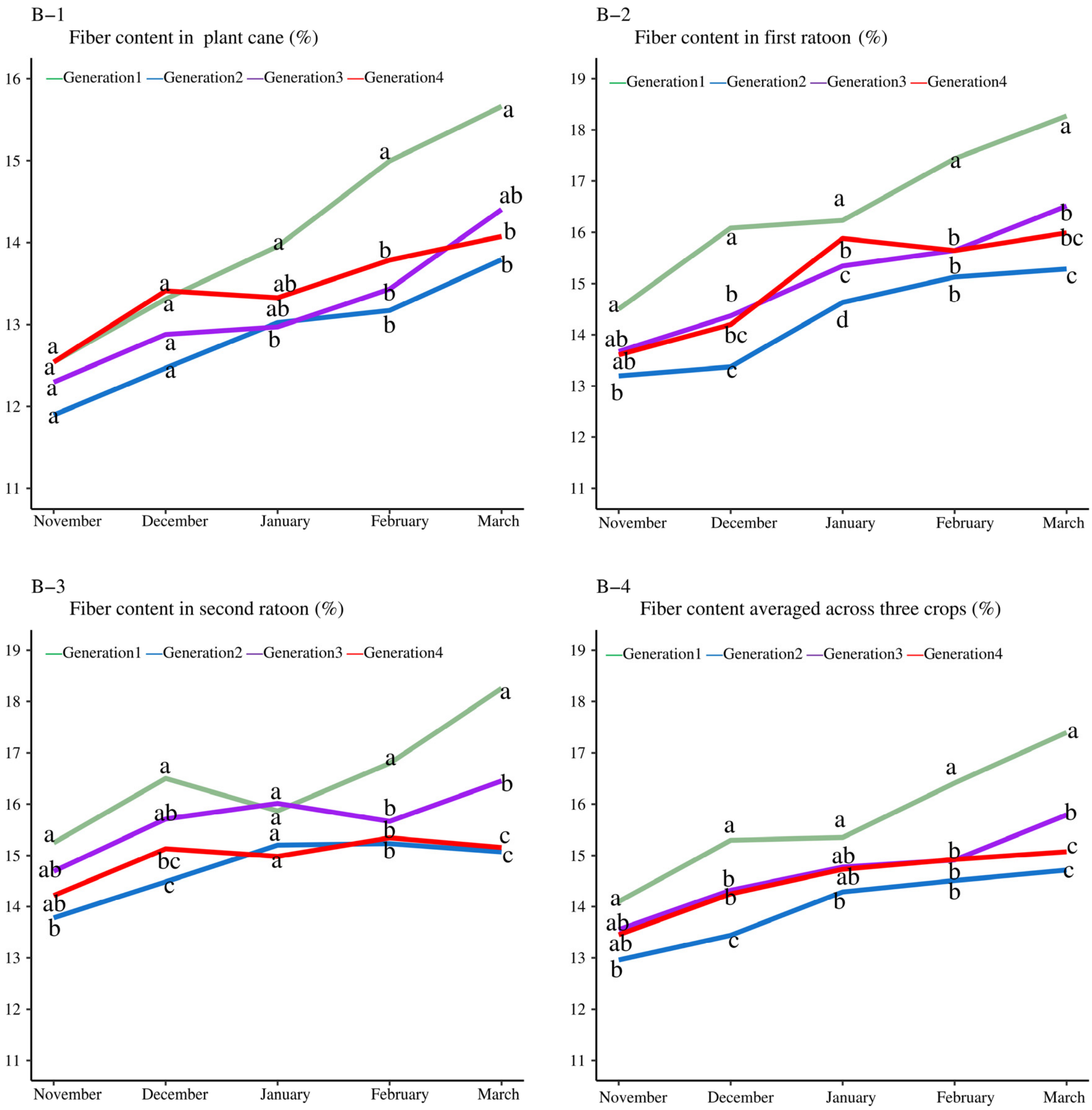

Figure 2. Analysis of the improvement in fiber content in four generations of sugarcane varieties in China. Monthly differences (November to March) of the four generations for planted cane (**B-1**), the first ratoon (**B-2**), the second ratoon (**B-3**), and the average content across three crops(**B-4**). a, b, c, d, $p < 0.05$, determined by the LSD test; the LSD test was across generations within a month.

3.4. Analysis of Improvements in the Sucrose Content of Sugarcane

The sucrose content of sugarcane showed an increasing trend with the development of improved generations in different months, and a similar trend was observed in the planted cane, the first ratoon, the second ratoon, and across all three crops (Figure 3). The average sugarcane sucrose content over 5 months increased with the progress of improved generations, and a similar trend was observed in the planted cane, the first ratoon, and the second ratoon.

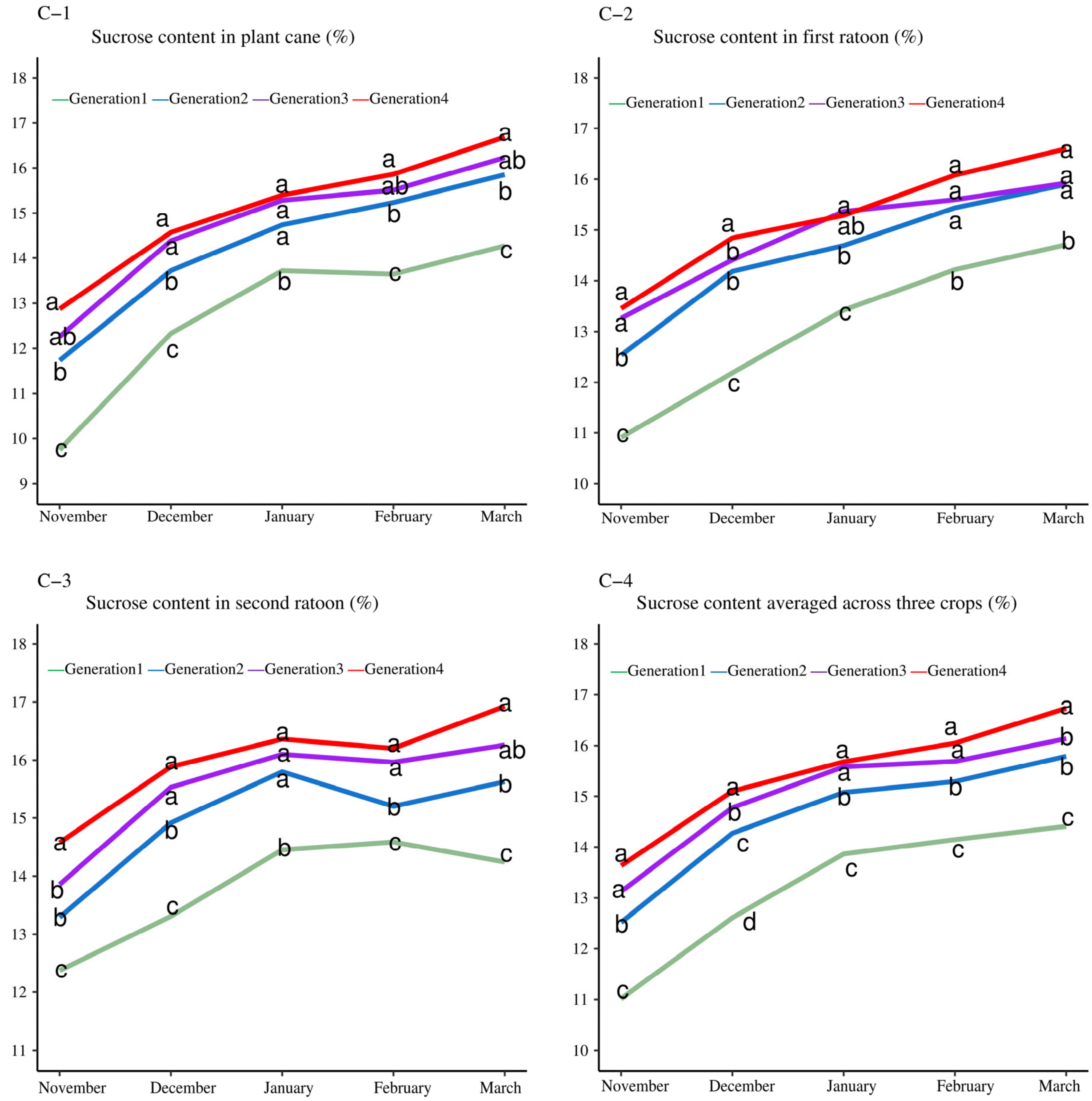

Figure 3. Analysis of the improvements in sucrose content in four generations of sugarcane varieties in China. Monthly differences (November to March) of the four generations for planted cane (**C-1**), the first ratoon (**C-2**), the second ratoon (**C-3**), and the average content across all three crops. (**C-4**). a, b, c, d, $p < 0.05$, determined by the LSD test; the LSD test was across generations within a month.

3.5. Analysis of the Improvements in Purity

The trends of the change in purity over 5 months varied among the four generations and among the different crops. With the growth of sugarcane, the purity of sugarcane continued to change, and the rate of the change in purity differed among the four generations. The purity of sugarcane in Generation 4 and Generation 1 was the highest and lowest, respectively (Figure 4).

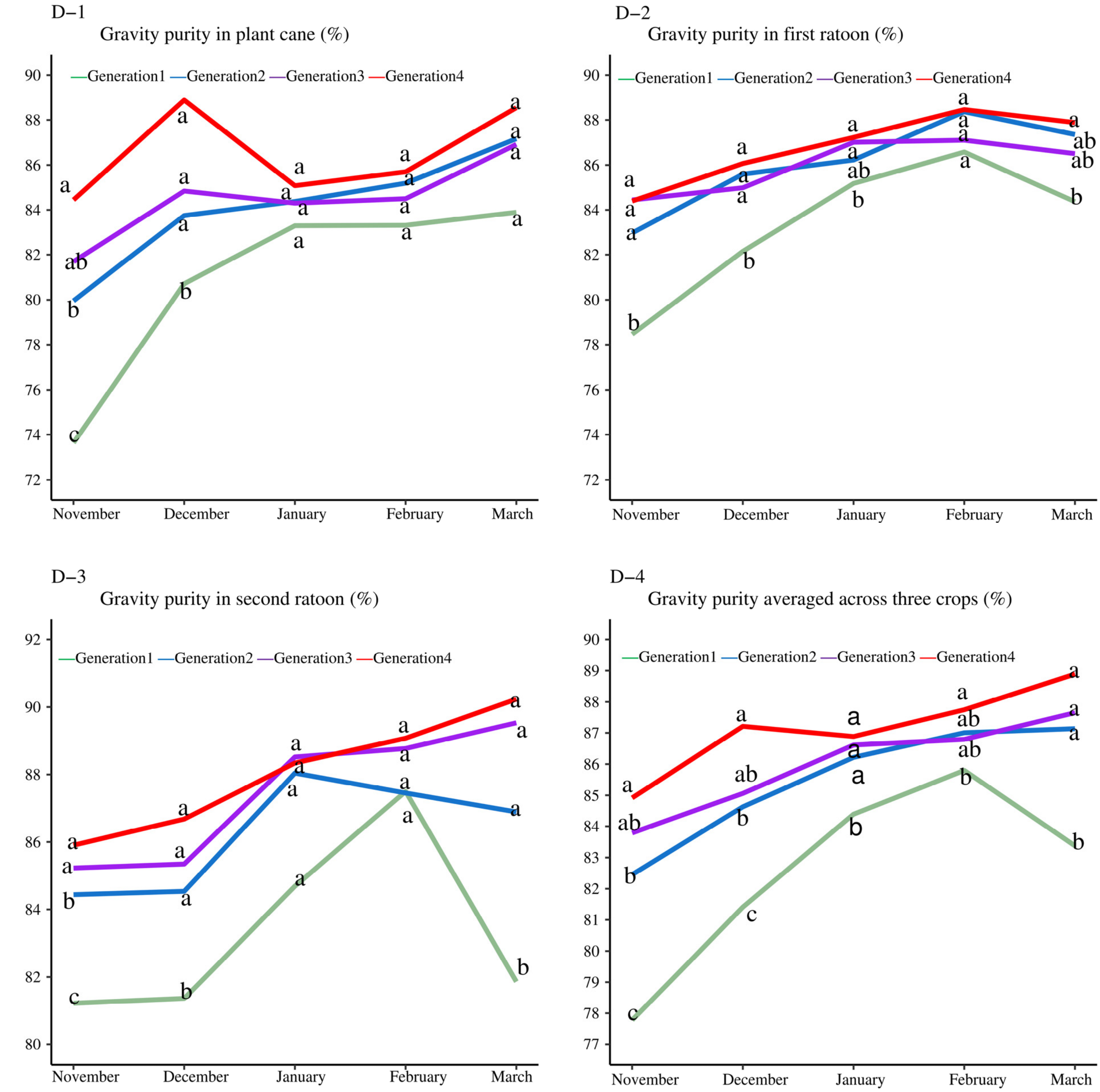

Figure 4. Analysis of the improvements in purity in four generations of sugarcane varieties in China. Monthly differences (November to March) of the four generations for the planted cane (**D-1**), the first ratoon (**D-2**), the second ratoon (**D-3**), and the average content across all three crops (**D-4**). a, b, c, $p < 0.05$, determined by the LSD test; the LSD test was across generations within a month.

3.6. Analysis of the Improvements in Technological Characteristics Based on the Development of New Varieties

The sucrose content of sugarcane and the sugar content of the juice increased with the development of improved generations ($p < 0.05$). There was a significant difference between alternate generations ($p < 0.05$) but no significant difference between adjacent generations ($p > 0.05$). The mean sucrose content of juice in Gen3 and Gen4 was significantly higher than that of Gen1 (Figure 5A,C). Fiber content showed no significant change across the four generations and there was no obvious change trend (Figure 5B). Purity showed an increasing trend with the development of improved generations, but the difference was not statistically significant ($p > 0.05$), except between Generation 4 and Generation 1 ($p < 0.05$) (Figure 5D).

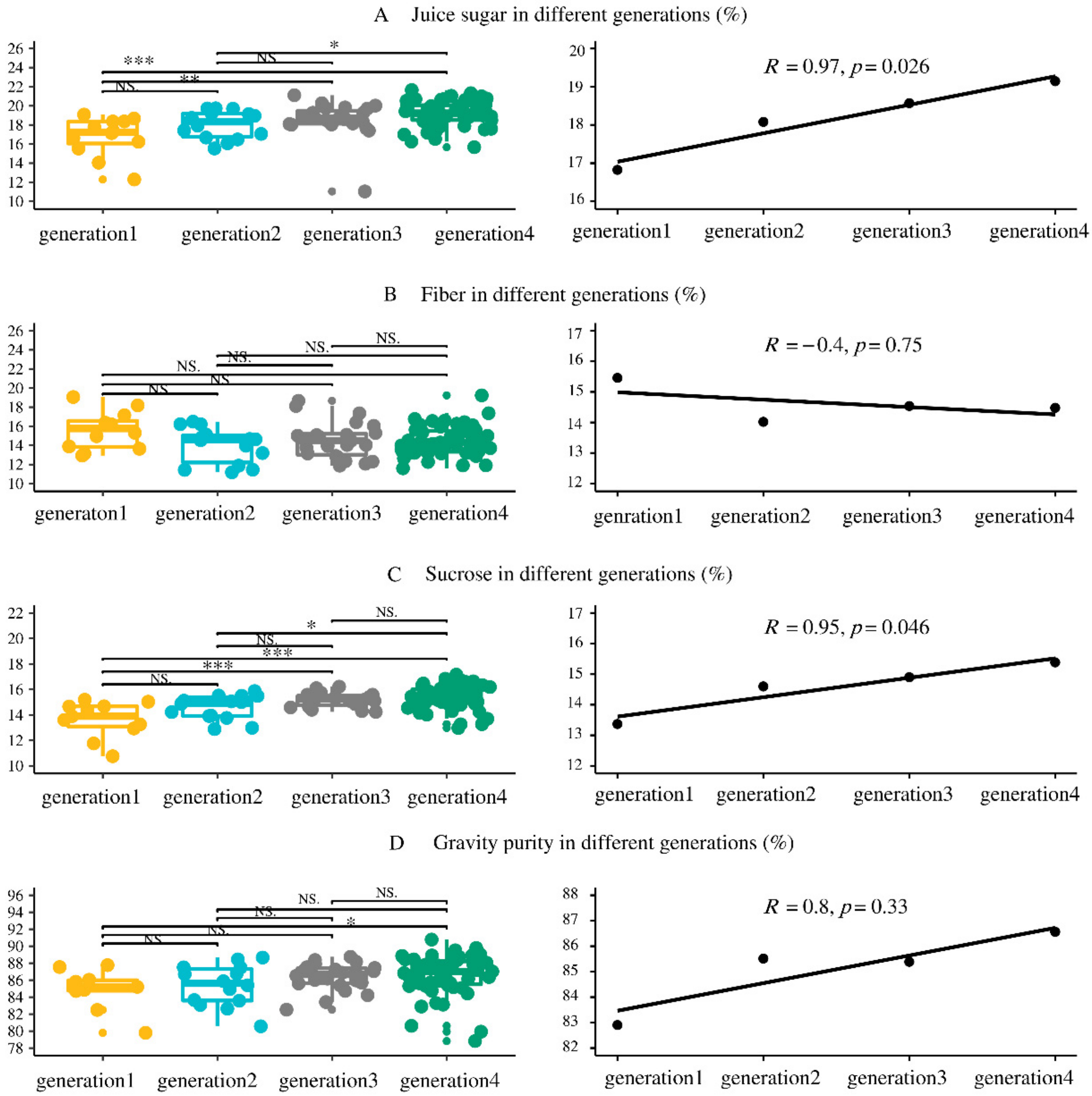

Figure 5. Differences among the four generations. NS, $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$, determined by the LSD test. In the linear regression analysis, R is the Spearman's correlation coefficient.

3.7. Improvements in Sugarcane Achieved through Cross-Breeding in China

Generation 4 showed significantly higher juice sugar content (2.35% higher; $p < 0.01$), sucrose content of sugarcane (2.06% higher; $p < 0.01$), and purity (3.69% higher; $p < 0.05$) than Generation 1. The fiber content of sugarcane in Generation 4 was 1.13% lower than that in Generation 1, but the difference was not statistically significant ($p > 0.05$; Figure 6).

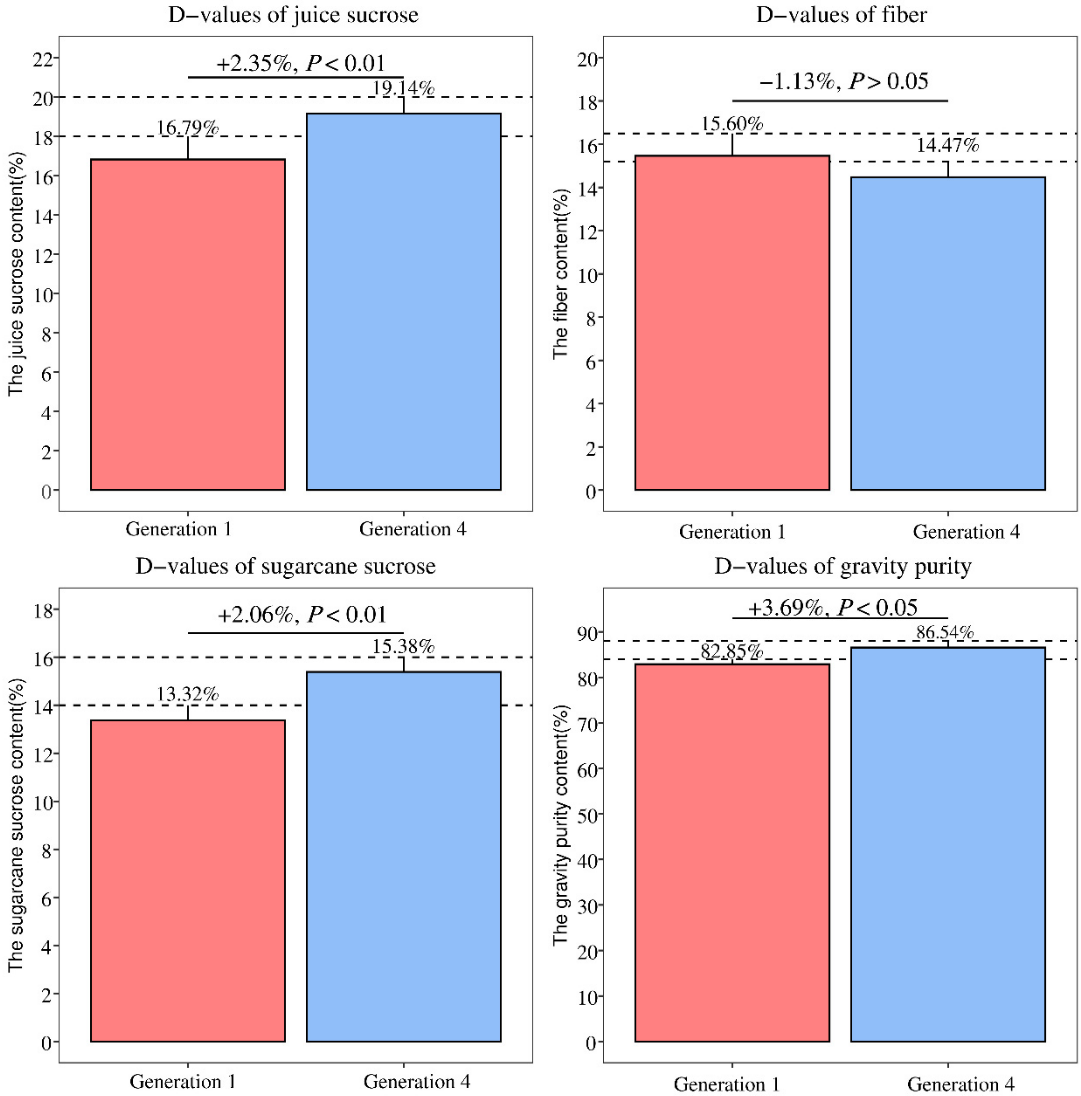

Figure 6. Differences (D-value) in the four technological traits (sucrose content of sugarcane, sugar content of the juice, purity, and fiber content) between Generation 4 and Generation 1 of sugarcane varieties in China, determined by the LSD test.

4. Discussion

4.1. Improved History and Classification of Improved Generations

Variety optimization is the core value used to test the effectiveness of sugarcane hybrid cross-breeding, and the division of generations is one of the main means used to study the improvements in sugarcane varieties. Burner made [22] a retrospective analysis of genetic advances from 1972 to 2012 near Houma, Louisiana, and found that the most recent generation, Generation 7, had a significantly greater normal juice Brix (NJB), normal juice sucrose (NJS), and normal juice purity (NJP) than Generation 2. In this study, we considered 20 years as a time node. The 100 sugarcane varieties bred in China between 1953 and 2010 and the 12 early interspecific hybrids varieties of sugarcane were divided into four improved generations to research the effectiveness of improvements in the technological characteristics of sugarcane varieties. In China, sugarcane varieties have been improved for four generations. Before 1934, sugarcane varieties in mainland China mainly included the original varieties such as Bamboo Cane and Lu Cane, which belong to the species *Saccharum sinense* Roxb [23]. Varieties such as POJ2725, POJ2878, and POJ2883 were introduced from the Philippines in 1934 and gradually replaced the original species in China. In 1937, CP2811 and CO290 were introduced, and CP290 was the main variety in the "foreign variety period". China soon replaced POJ2878 with the varieties F108 and F134, which were bred in 1947 by the Taiwanese breeding institute; this period was called the "F134 period". In 1953, the Sugarcane Breeding Farm in Hainan was established, which started sugarcane hybrid cross-breeding in China [24].

The period from 1953 to 1970 marked the initial stage of sugarcane hybrid cross-breeding in China. Chinese sugarcane breeders began to innovate and created a sugarcane breeding system with CP (a hybrid parent series bred by the US sugarcane breeding institute), F (a hybrid parent series bred by Taiwan's (China's) sugarcane breeding institute), and CO (a hybrid parent series bred by the Indian sugarcane breeding institute) series of germplasm as the core parents, which had a far-reaching impact on sugarcane breeding in China [16]. To date, new Chinese sugarcane varieties still generally have CP, F, and CO series ancestors, and the breeders have a special affection for these parent varieties. The varieties bred in this period mainly used F, CO, and CP series as parents, e.g., GT60289, GT60149, HN5612, YT56268, GZ64137, MT70611, and CT57416 (Table 1). These varieties generally exhibit large stems, early maturity, and good ratooning ability, which have accelerated the process of sugarcane breeding in China. These varieties were not discarded on a large scale; F134 remained the main sugarcane cultivar in mainland China until 1980. One of the main reasons was that the selected parents are mostly limited to F134, CO419, and CP4950 [25].

The period from 1971 to 1990 was called the second stage of improvement in sugarcane cross-breeding in China. During this period, breeders began to focus on the cross-utilization of self-breeding varieties and used excellent sugarcane varieties as parents to select new sugarcane varieties, e.g., YT85177, GT86267, GT895, and YZ71388 (Table 1). During this period, the available sugarcane parent resources in China became increasingly more abundant; for example, the creation of the YC series of germplasm and their application to sugarcane cross-breeding resulted in several varieties such as CT89103, GN89131, and YT89240 [26]. Moreover, this period also marked the establishment of the largest area planted to sugarcane and most breeding institutions in China. In addition to Guangxi, Yunnan, and Hainan, Guangdong, Fujian, Jiangxi, Sichuan, Guizhou, and Hunan provinces are still the main sugarcane-producing areas in China. Cultivated varieties such as CT, MT, GZ, and HN still occupy a significant proportion of sugarcane production; thus, this period exhibited dynamic development and the coexistence of multiple sugarcane varieties.

The period from 1991 to 2010 was a critical period for the development of the technological structure of sugarcane breeding in China. The area of sugarcane plantations in China continued to decline, the main sugarcane-producing areas continued to shrink, and the technological structure tended to be stable and ideal. During this period, the main varieties bred in China belonged to the GT, YT, YZ, FN, LC, and ROC series, e.g., GT31, GT35, YT00236, YT93159, YZ0551, ROC1, ROC10, ROC22, and ROC25, which have the characteristics of high yield, high sugar, and good ratoons. Since the cultivation of ROC22 in 1997, it has occupied the dominant position in China's sugarcane plantations for a long time, occupying approximately 70% of the area planted to sugarcane [17]. Since 2020, ROC22 was gradually replaced by varieties such as GT35, GT42, GT44, LC05136, YZ0551, YZ081609, and YT00236. Mainland China has entered the dominant period of self-breeding [27].

4.2. Improvements in Sugarcane's Sucrose Content, Sugar Content of Juice, Fiber, and Purity

Since the establishment of a sugarcane hybrid breeding system in China, high yield and high sugar content have always been the objectives of sugarcane breeding. Breeders regard significant improvements in the sugar content as the primary goal of breeding breakthrough varieties of sugarcane. The main sugarcane-producing countries in the world, such as the United States, Australia, Brazil, Thailand, and India, also consider improvements in sugarcane's sugar content as the primary goal of cross-breeding sugarcane. Therefore, they have established advanced breeding methods and sophisticated breeding systems.

For example, early selection improves early-stage clonal selections in sugarcane breeding [28]. Recurrent selection increases the sugarcane's sugar content during breeding [29]. Breeding for disease resistance effectively alleviates the occurrence of sugarcane diseases and has expanded the cultivation area of certain varieties [30]. High-throughput breeding increases breeding efficiency and is increasingly being applied to various aspects of sugarcane breeding research [31]. Parental innovation has established several excellent parents for sugarcane hybridization, which have improved the level of sugarcane breeding [32]. In China, some achievements have been made in terms of improvements in the main technological characteristics of sugarcane such as sucrose content. In the present study, the sucrose content of sugarcane and cane juice increased with the development of the improved generations. However, this increase has been gradual; in general, the difference between two adjacent generations was not significant, but the difference between distant generations was significant. Overall, the greatest improvement in Chinese sugarcane varieties was observed in sucrose content. The most recent generation of sugarcane varieties include the main cultivated varieties in China's sugarcane region, and their sucrose content was more than 2% higher than that of the original varieties such as the CO and POJ series. Sugarcane purity did not improve continuously, but the G4 varieties showed approximately 3% higher purity than the original innovation varieties (Figure 6). However, sugarcane fiber content did not vary significantly among the generations; although it decreased every generation after Generation 1, the decline was not significant. This finding is explained by the fact that when breeding sugarcane varieties, breeders have focused excessively on improving the sucrose content rather than on improving the fiber content. However, for energy sugarcane, improving the fiber content is one of the main purposes of breeding. A type of cane with a higher concentration of fiber has been developed and cultivated, called energy cane. This cane type has more fiber than sucrose in its composition, which makes it better for producing energy and ethanol, but inappropriate for sugar production [33]. Different types of sugarcane varieties can be defined on the basis of the relative proportion of sugar and fiber content in the stem, and sugarcane with high fiber is now being recognized as a potential dedicated energy crop, even in regions where its cultivation has not been a common practice [34]. Therefore, in the future, sugarcane fiber content should become an important consideration in the breeding of sugarcane varieties, no matter whether it is considered as an energy material or for mechanized harvesting.

4.3. Selection of the Parents of Commercial Hybrid Varieties of Sugarcane

As shown in Table 1, the parents of commercial varieties in Generation2 (from 1953 to 1970) in China mainly included the CO, F, and CP varieties. At that time, sugarcane breeding did not have a clear objective and mainly aimed at improving the CO, F, and CP varieties. Therefore, although the sucrose content of Generation 2 increased at the population level, the improvement was not significant, which is why F134 continued to represent approximately 50% of the national sugarcane production area until 1978 [35]. From Generation 3 and onward, sugarcane breeders began to develop their own breeding system, and self-breeding varieties were used as hybrid parents to purposefully improve commercial varieties. The system differed from the recurrent selection technology adopted by the United States, which established its own parent system for targeted sugarcane breeding [36]. The Chinese sugarcane hybrid cross-breeding system still had certain limitations, which were mainly reflected in the varieties bred by using older hybrid parents such as CO, F, and CP. Therefore, although the sucrose content of the Generation varieties was significantly higher than that of Generation 1 varieties, this improvement remained non-significant. The parents of certain Generation 4 hybrid varieties are old varieties, many of which were used in Generation 2 or even G1. For example, the parents of YZ91510 are CP4950 and GT69435. Between 1990 and 2010, the parent varieties used in breeding the Generation 2 or Generation 1 varieties were still used as parents in the breeding of new sugarcane varieties in China. These parents have been used repeatedly for decades and will continue to be used; for example, CP4950 has been used as the core parent from

Generation 1 to Generation 4. Many other variety resources such as CP721210, ROC5, and CO1001 have been reused in various stages of sugarcane cross-breeding in China (Table 1). Therefore, the main reasons for the relatively slow progress of improvements in sugarcane varieties in China are that the goal of sugarcane breeding was unclear, a core parent bank in the real sense had not been established, and the selection of parents was random and subjective. Earlier experts stated that whether a hybrid crossing combination had good offspring mainly depended on the trial in the first few years, and if there were no good offspring in the first few years, it was futile to repeat the trial [15]. Therefore, it was believed that a combination should not be repeated for many years but tested only for a few years. In recent years, breeders have begun to realize the importance of parental innovation, and the conscious use of newer commercial varieties with excellent performance as hybrid parents has produced good results [37]. For example, YZ081609 [38] belongs to the latest generation of sugarcane varieties cultivated with YZ94143 as the male parent and YT00236 as the female parent, and these parents are excellent commercial varieties cultivated in recent years [16]. Many varieties, such as LC05136, GT35, YT00236, and ROC22, are not only the main production varieties but also the core parents used for improving sugarcane varieties. This practice has enriched the parent germplasm bank of the Hainan Sugarcane Breeding Farm and has provided more and better parents for selection.

5. Conclusions

Hybrid breeding has significantly improved the sugar content of juice, the sucrose content of sugarcane, and purity and decreased the fiber content compared with the varieties developed earlier. With the development of improved generations, the sucrose content of sugarcane, the sugar content of the juice, and the purity of sugarcane have continued to improve, and the improvement has been significant between generations. The fourth generation showed 2.06% higher sugar content in the juice, 2.35% higher sucrose content I the sugarcane, 3.69% higher purity, and 1.13% lower fiber content than the first generation. We suggest that the commercial sugarcane varieties in China may be improved by selecting the right hybrid combination as parents, especially by increasing the use of the existing main cultivated varieties as parents.

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