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REVIEW

SUSTAINABLE SUGARCANE CROPPING IN CHINA

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KEYWORDS

sustainable sugarcane cropping, soil health, rotation and intercropping, soil acidification

HIGHLIGHTS

- Cost escalation and declining profits evident in sugarcane production in China.
- Monoculture and fertilizer overuse causes poor soil health, crop productivity plateau.
- Matching crop nutrient demand and supply key to recovery of sugarcane soils.
- Inorganic inputs need to be replaced with organic sources to restore soil health and sustainability.
- Integrated multidisciplinary solution for sustainable sugarcane cropping system needed.

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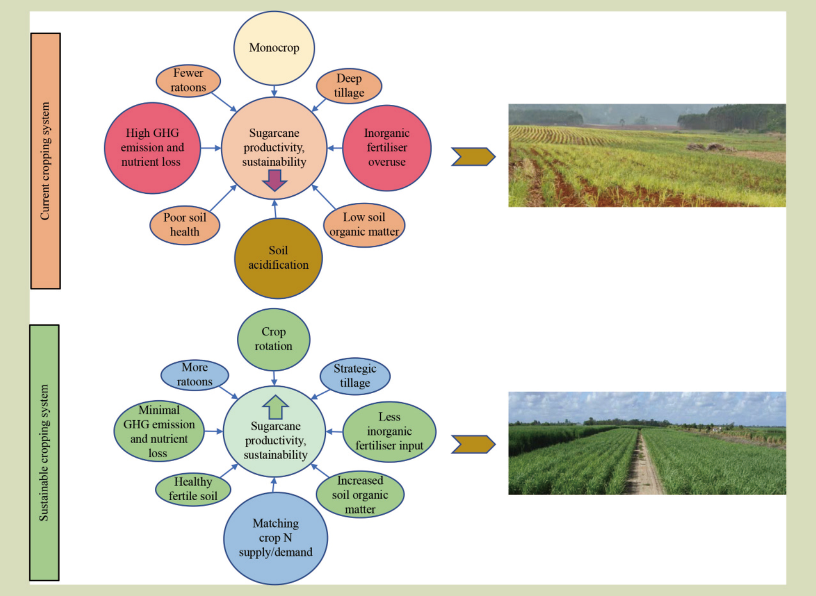
GRAPHICAL ABSTRACT



ABSTRACT

Demand for sugar is projected to grow in China for the foreseeable future. However, sugarcane production is unlikely to increase due to increasing production cost and decreasing profit margin. The persisting sugarcane yield plateau and the current cropping system with fertilizer overuse, soil acidification and pests and diseases remain the major productivity constraints. Sugarcane agriculture supports the livelihood of about 28 million farmers in South China; hence, sustaining it is a socioeconomic imperative. More compellingly, to meet the ever-increasing Chinese market demand, annual sugar production must be increased from the current 10 Mt to 16 Mt by 2030 of which 80% to 90% comes from sugarcane. Therefore, increasing sugar yield and crop productivity in an environmentally sustainable way must be a priority. This review examines the current Chinese sugarcane production system and discuss options for its transition to a green, sustainable cropping system, which is vital for the long-term viability of the industry. This analysis shows that reducing chemical inputs, preventing soil degradation, improving soil health, managing water deficit, provision of clean planting material, and consolidation of small farm holdings are critical requirements to transform the current farming practices into an economically and environmentally sustainable sugarcane cropping system.

1 INTRODUCTION

Sugar is the sixth largest agricultural export commodity and the fourth largest source of human dietary energy globally, and its demand has been increasing for decades[1]. This ongoing demand led to the expansion of sugarcane agriculture and sugar industries around the world. The same trend was also evident in China. Chinese sugar production, however, remains insufficient to meet the local demand, which is projected to increase to 16 Mt by 2030[2]. China is now the second largest importer of sugar. Sugarcane accounts for 87% of sugar produced in China in 2020[3], and there is little opportunity for increasing its production area due to competition for land from high-value crops. Thus, increasing crop yield and crop productivity becomes an imperative to sustain the local sugarcane industry.

Sugarcane is relatively easy to grow. It tolerates a wide range of environmental conditions, is quite resilient under drought, and often is grown on less fertile and marginal land with reasonable yield[4]. However, sugarcane is highly responsive to nitrogen fertilizer and irrigation, and with water and fertilizer inputs crop productivity can be increased dramatically[5,6]. In China, owing to the limited availability of irrigation water where sugarcane is grown, farmers mostly rely on the liberal use of fertilizers, especially N fertilizer, to boost cane yield. This overuse of N fertilizer and decades of monoculture coupled with suboptimal cropping system and poor crop husbandry led to extensive soil degradation and yield plateauing in all sugarcane production regions in China[7]. Replacing mineral N with organic sources, halting soil degradation, regaining soil health and matching N supply and crop N demand remain the key to develop a robust and sustainable sugarcane cropping system. Such cropping system transformation is currently underway in cereal crops in China and elsewhere[8,9]. Also, a remarkable leap in agricultural production theory, technology and crop production system innovations has occurred in many advanced economies, including China, over the last decade[10–12]. These innovation opportunities to transform Chinese sugarcane industry into an economically and ecologically sustainable agricultural production system form a key theme of this review and they are discussed below. However, before going further on this aspect, it would be useful to introduce sugarcane crop, its production and sugarcane industry in general from a global perspective first. This will be followed by an analysis of sugarcane production in China to understand where the Chinese sugarcane cropping system stands now and what could be done to transform it into a sustainable crop production system.

2 SUGARCANE CROP AND A GLOBAL PERSPECTIVE OF SUGARCANE AGRICULTURE

Sugarcane is a perennial crop harvested every 10–12 months in most countries except for a very small area in subtropics where it takes 18–22 months to reach maturity. In many countries sugarcane is grown and harvested annually for many years until the stand becomes uneconomical. The crop will then be plowed out and plant a new crop, and the duration between planting and replanting can be 2–10 years, depending on the country. More than 70% of sugarcane worldwide is rainfed and is grown in regions with annual rainfall ranges between 800–1700 mm. Being a C4 tropical grass, it is one of the most productive plants, accumulating biomass at a rate as high as 550 $\mathrm{kg \cdot ha^{-1} \cdot d^{-1}}$[13]. It is also unusual in that, on a dry matter basis, it accumulates up to 600 mg sucrose per g mature stalk[14], one of the highest sugar accumulations recorded for a plant species. Sugarcane grows best at around 32 °C and ceases to grow when mean daily temperature is between 10–15 °C, depending on the cultivar and location[15]. Sugarcane thrives well under high light intensity, long periods of radiation and irrigation, as shown by commercial cane yield reaching 210–250 $\mathrm{t \cdot ha^{-1}}$ cane[13] in fully irrigated crops in Australia and Colombia, the countries that receive most sunshine among the sugarcane growing nations. It is also highly responsive to nitrogen input[16], which explains the excessive N input in sugarcane crops occurring in many countries[6,7]. Sugarcane though tolerates abiotic stresses normally experienced in commercial crop production conditions, its growth is highly sensitive to water deficit[5] and frost[17], the key environmental determinants of sugarcane productivity worldwide. Many pests and diseases affect sugarcane crop and they vary from country to country, and even between different regions within a country[18,19].

Sugarcane is an established tropical and subtropical sugar crop grown in about 105 countries[1]. It accounts for more than 80% of sugar produced globally and is now the second largest bioenergy crop in the world[1,7]. Globally, sugarcane production has increased by about 44% since 2000[1], mostly by expanding sugarcane cultivation in Brazil, India and Thailand. A quarter of cane sugar produced now is used for biofuel production. In addition to sugar and bioethanol, sugarcane milling produces a large quantity of lignocellulosic fiber, called bagasse, as a byproduct, which is used for generating electricity[20]. In Brazil, the largest producer of sugarcane in the world, 28 GL of bioethanol and about 60 TWh of electricity were produced from sugarcane in 2020, making the crop a significant contributor of sustainable green agriculture[21].

Worldwide, sugarcane is grown in about 29 Mha mostly in relatively low fertile soil. It produces the greatest harvested biomass, for instance, about 1.9 Gt cane in 2019, compared to all other crops globally[1]. Brazil, India, China and Thailand are the top four sugarcane producing countries with most of the production, nearly 60%, coming from Brazil and India[1]. In all the major sugarcane growing countries, commercial sugarcane cultivars are continuously replaced by new clones produced through crossbreeding. It takes about 10–12 years to produce a new cultivar. Most cultivars stay in commercial production for about 5–10 years, and these are often lost due to pests and disease pressure and limited regional adaptation. Sugarcane shows high genotype-by-environment (G×E) interactions, and hence, cultivars bred for a country rarely succeed as commercial cultivars transnationally[4,22].

Historically sugarcane was harvested manually, with the trash (leaves and shoot top) burnt either before or after harvest. Manual harvesting is still practiced in most countries, but with the rising labor shortage and labor cost, sugarcane harvesting and transportation are mechanized fully in countries such as Australia, Japan and USA, and at varying levels in many other countries including Argentina, Brazil, China, India and Thailand[3,23]. The mechanized harvesting facilitated cutting sugarcane without burning trash, leaving green leaves and the shoot top in the field. This environmentally-friendly practice, called green cane trash blanketing, is now becoming common even in countries with manual harvesting.

While there is considerable similarity in cultivar development methods among sugarcane growing countries, remarkable variation occurs for sugarcane cropping systems and crop management practices. It varies from continuous monoculture to rotation and intercropping, narrow to wide row spacing, and a crop cycle comprising plant crop (first crop after planting) and one ratoon crop through to one with plant and several ratoon crops (crops following plant crop)[23,24]. For instance, in some South-east Asian countries, sugarcane needs to be replanted after the first ratoon crop whereas in Australia, despite mechanical harvesting, five to six ratoon crops before replanting is normal. Smallholder farming remains a significant feature, and productivity drag, of sugarcane agriculture in most developing countries with average farm size less than 0.5 ha.

Currently the global average sugarcane yield is 70.6 $\mathrm{t \cdot ha^{-1}}$ cane[1], which is far below than the estimated potential yield of 381 $\mathrm{t \cdot ha^{-1}}$, the commercial crop maximum yield of 260 $\mathrm{t \cdot ha^{-1}}$ recorded in Brazil and the experimental maximum yield of 299 $\mathrm{t \cdot ha^{-1}}$ reported by the Brazilian sugarcane breeding program RIDESA Experimental Station in Bahia, Brazil[13]. Also, it is worth noting that commercial yield of > 200 $\mathrm{t \cdot ha^{-1}}$ is routinely produced by some of the best managed sugarcane farms in most productive sugarcane growing regions in Australia. This large yield gap clearly illustrates the potential for substantial productivity gains through continued genetic improvement and optimization of cropping systems globally.

3 SUGARCANE CULTIVATION IN CHINA

Sugarcane is a major and a strategic crop of China, and sugar is one of the important agricultural industries in southern China[25,26]. Its humid, subtropical climate and ample rainfall make the region the most ideal location for sugarcane agriculture. Until mid-1980s sugarcane was grown in 11 provinces or autonomous regions, including Fujian, Guangdong, Guangxi, Guizhou, Hainan, Hubei, Hunan, Jiangxi, Sichuan, Yunnan, and Zhejiang[26]. However, a drastic decline in sugarcane production has occurred over the last decade and its commercial cultivation is now limited to Guangdong, Guangxi, Hainan and Yunnan. In the 2013 cropping season, sugarcane was cultivated on 1.71 Mha, but its production has declined to 1.16 Mha by 2020/2021 mainly due to competition for land from other crops[27]. In 2020/2021 cropping year China produced 9 Mt of sugar from 73 Mt of cane harvested. In the same cropping year, the average cane yield was 63 t·ha^{-1}, which is significantly lower than the world average of 71 t·ha^{-1}[27]. This unusually low yield was caused by a prolonged dry season in the cropping season. Nationally about 10% of the total sugarcane production receives supplementary irrigation, making local sugar industry vulnerable to recurring drought[25].

Currently Guangxi accounts for about 68% of sugarcane production in China, with the remaining distributed among Guangdong, Hainan, and Yunnan[27]. Despite long-running multiple sugarcane breeding programs spread across all sugarcane growing provinces, sugarcane yield and sugar recovery in mills did not make any remarkable improvement for a long time. This yield plateauing appears to be due to a combination of poor crop management, persisting soil constraints and slow genetic gain through breeding[25,26,28].

Sugarcane agriculture and sugar production are among the key pillars of social and economic development of Guangxi and Yunnan[26]. The sugar industry is the main source of income for many regional communities. For example, in Guangxi alone, it provides direct employment to about 20 million farmers, and people in 50 counties are directly relying on sugar industry for their income. However, increasing cost of production and shrinking profit from sugarcane is driving many farmers to move to other crops. Currently sugarcane production costs in China are estimated to be about 5400 CNY·ha^{-1}[27], which is relatively high compared to other countries. Therefore, any effort to improve sugarcane crop yield and sugar industry productivity will have a direct positive impact on the rural economy, regional development, and reduced import dependence.

4 CLASSIFICATION OF CHINESE SUGARCANE CULTIVATION AREAS INTO MEGA-REGIONAL PRODUCTION ZONES AND THEIR ECOLOGICAL ATTRIBUTES

Unlike grains or other short-duration crops, sugarcane is a 12-month crop in most production regions, and it experiences all seasonal effects before completing a cropping season. Also, sugarcane stems being the harvested product, yield is determined by its growth potential. Hence, it is not surprising that G×E interactions influence sugarcane productivity than any other crop production component[29]. This is also evident in Chinese sugarcane production system[29,30]. Recognizing the importance of G×E on sugarcane productivity, most well-managed breeding programs use regional selection to produce regionally-adapted cultivars. This has significantly reduced yield gap and increased overall crop productivity in many countries[3,4,23].

In China, for a long period sugarcane breeding programs followed a wide adaptation selection strategy to produce cultivars with broad environmental adaptation. However, the focus has now shifted toward regional selection, founded on mega-regional production zones defined by ecological principles[3,29,30]. This regional production zone classification and characterization will not only help develop high performing cultivars suited for each mega-environments, but will also greatly aids in optimizing cropping systems to maximize crop productivity and facilitate sustainable cultivation. Based on a comprehensive ecological analysis of the entire sugarcane production areas in China, it is classified into three major ecological production zones: (1) the Southern China Inland Sugarcane Production Zone covering a large portion of Guangxi comprising regions such as Baise, Hechi, Laibing and Liuzhou; (2) the South-western Plateau Sugarcane Production Zone comprising regions such as Baoshan, Kaiyuan, Lincang and Ruili in Yunnan; and (3) the Southern China Coastal Sugarcane Production Zone comprising regions such as Fuzhou and Zhangzhou in Fujian, Suixi and Zhanjiang in Guangdong, Chongzuo in Guangxi, and Lingao in Hainan[29,30].

Ecologically, these three regions vary significantly[29]. For instance, the South-western Plateau is much drier than other two zones, receiving 700–1300 mm annual rainfall whereas Southern China inland zone annual precipitation varies between 1100–1700 mm. Also, South-western Plateau with more loamy soils and steep hillslopes is quite distinct to Southern China Inland and Southern China Coastal zones geologically; the latter two are characterized by more sandy, red and yellow soils with relatively more flat lands. Similar to soil types and precipitation large variation for annual day length, ranging from 1450 to 2350 h, exits among these three regions. Considering this ecological variation among production regions, it is very important to optimize cropping systems suited for local production environment and locally adapted cultivars to maximize sugarcane crop yield and sustainability.

5 SUGARCANE CROPPING SYSTEMS IN CHINA

5.1 Sugarcane cultivation and crop management

Sugarcane is a perennial monoculture crop in China in > 95% of the production regions, and it takes about 12 months to mature. Hence, a sugarcane crop cycle, from planting to plowing out a crop, normally constitutes a plant crop and a single or multiple ratoon crops. The number of ratoon crops is dictated by the economics of production as yield gradually declines with increasing ratoons[31]. Plant and two ratoons is common in most production regions of China[28], but in high-yielding relatively flat and fertile land three ratoons are not uncommon. Sugarcane is planted mostly in spring though it is also planted in autumn, and even in winter in some locations[26]. For commercial crop production, summer planting is rare. Mature crop is harvested manually between November and February, depending on the cultivar maturity type: early, midseason or late maturing[25,28]. Currently, mechanical harvesting is limited to less than 5% of production area nationally[28].

In China, sugarcane can be planted in all seasons, depending on the region[26]. The two most common sugarcane planting seasons are autumn planting starting in September extending to late November and spring, with autumn-planted crop harvested up to 15 months after planting giving it the highest sugar yield compared to crops planted in other seasons. Also, autumn-planted crops tend to have stable yield and early sugar accumulation. Crops are grown in different planting configurations, either with narrow- (80–90 cm) or wide-row (150 cm) spacing, in different regions[26].

Sugarcane is vegetatively propagated and grown mostly in hillslopes. For planting, both whole stem (stick planting) and billets (stem cuttings with 2–3 buds; billet planting) are used and the sowing rate varies between different regions, but billet planting takes about 12 t·ha^{-1}[32,33]. The quantity of seedcane (planting cane) needed to establish a commercial crop is dependent on the availability of soil moisture (or provision of irrigation), time of planting, farm location, soil type and cultivar. Deep plowing to prepare land for planting is a common practice, and land preparation and almost all crop management practices are now completely mechanized. About 80% of the entire sugarcane crop in China is fully rainfed with no opportunity for supplementary irrigation, and hence, initial shoot growth in spring-planted crops heavily relies on the stored soil moisture from autumn rain. Use of approved clean seedcane (planting material without pests and pathogens) is an important factor determining crop productivity and the duration of crop cycle[32,34]. Nitrogen, phosphorous and potassium fertilizers, and pesticides to control stem borer, are applied at the time of planting. Seedcane is planted manually in rows with 80–90 cm interrow spacing in most regions and planted rows are covered with plastic film to conserve soil moisture.

Application of fertilizers and control of pests and pathogens are the key crop management activities during crop growth. A recent industry-wide farmer survey showed large variation in the amount and method of application of fertilizers in all major sugarcane production regions in China[7,16]. On average, in each cropping season, famers apply 560 kg·ha^{-1} N, 120 kg·ha^{-1} P, and 220 kg·ha^{-1} K as 2–3 split applications over the first 6 months starting from planting or shortly after harvest[7,32]. Increasingly, mineral fertilizers are applied as compound fertilizers that include pesticides to control stem borers. Organic amendments, such as farm manure and sugar mill byproducts (bagasse, mill filter cake and vinasse), are applied to improve soil fertility[26]. Banning of trash burning and the widespread practice of green cane harvesting led to trash retention on farm, which is improving soil health, weed control and soil moisture retention[35,36]. With clean seedcane of locally adapted high-yielding cultivars for new planting and following the best management practices for fertilization, soil health, weed and pest management, harvesting and trash retention in the harvested field, plant and up to four ratoon crops before replanting is now commonplace in well-managed farms. This indicates the untapped potential of improved science-based crop management practices in lifting the productivity, profitability and sustainability of sugarcane crops in China.

5.2 Sugarcane intercropping and crop rotation

The economic and environmental potential of sugarcane intercropping and crop rotation has been researched extensively in many countries including China[37,38]. Intercropping improves soil fertility and soil biology, reduces the risks of pests, diseases and weeds, stabilizes yield and increases land use efficiency[39]. The long growth period, wide row spacing and the relatively slow canopy filling of sugarcane are well suited for intercropping[40,41]. Sugarcane intercropping is mostly practiced by smallholders and subsistence farmers in developing countries. Successful intercropping of sugarcane with beans, chilly, cowpea, maize, onion, peanut, potato, soybean, sweet potato and many green manure plants have been reported[42,43]. However, intercropping of sugarcane is not widely practiced. Where analyses were done, sugarcane intercropping was found to be economically non-viable in at least half of the cases, and where economic benefits were accrued, they were very marginal[44–46]. Additional costs and equipment, lack of market access, economic risks, a lack of technical expertise for designing region-specific intercropping systems, and insufficient appreciation of ecological benefits of intercropping were the major reasons for poor adoption of intercropping systems in sugarcane. In China, sugarcane rotation is only rarely practiced.

6 MAJOR CROP PRODUCTIVITY ISSUES OF CHINESE SUGARCANE INDUSTRY

Chinese sugarcane industry is now experiencing the difficulties normally encountered during the transition from a government-protected establishment to a market-driven business. The combination of rising labor and land cost, dwindling labor pool, high sugar production cost and declining profit, lack of minimum purchase price in all sugar-producing provinces except Guangxi, import competition and low crop productivity are forcing sugarcane farmers to more profitable crops. Cost of sugar production in China, about 5400 CNY·t^{-1} of sugar, is currently one of the highest in the world. Labor shortage will continue and will get worse with time. The high cost of sugarcane and inefficiencies in sugar production are straining the business of most sugarcane mills as well. Thus, sugarcane production cost must be reduced to make the industry economically sustainable.

This situation is exacerbated by low cane and sugar yields that have persisted for a long time. For example, more than 30 new sugarcane cultivars have been released in China over the last decade with no significant improvement in sugar yield achieved[3]. This suggests that little genetic improvement of sugarcane is being realized through the current breeding efforts in China. This is also reflected in the widespread occurrence of sugarcane pests and pathogens that are mostly managed through cultivar resistance in other countries[47]. For most crops, about half of the advances in realized yield potential of new varieties come from genetic improvements and half through cropping systems. Sugarcane cropping systems in China are far from optimal in various ways. Given the disturbingly low rate of genetic gains through crop breeding, improving cropping systems is imperative for increasing sugarcane crop productivity.

7 DEVELOPING SUSTAINABLE CROPPING SYSTEMS FOR CHINESE SUGARCANE INDUSTRY: CURRENT CONSTRAINTS AND POSSIBLE SOLUTIONS

A cropping system that maximizes the yield potential may not necessarily be environmentally benign and sustainable. Indeed, often it is not, and the current sugarcane production system in China is no different. Long-term monoculture of any crop will lead to soil degradation unless appropriate crop and soil management measures are in place to preserve soil health. The challenges of current sugarcane production system in China are: (1) soil acidification and all the attendant plant nutritional and soil property anomalies causing significant yield loss; (2) lack of standardized spatial configuration of sugarcane planting; (3) low soil organic matter; (4) high heterogeneity of farming landscape topography and regional climate; (5) relatively high greenhouse gas (GHG) emissions; (6) recurring drought; (7) short crop cycle with fewer ratoons and reduced crop productivity; (8) lack of crop rotation; (9) limited availability and use of clean sett; (10) deep plowing for land preparation; (11) plastic film mulching; and (12) limited choice of locally adapted high-yielding cultivars. Here we examine the sugarcane cropping system-related issues and discuss strategies, their agroecological implications, for developing a sustainable sugarcane production system. A list of research, development and adoption targets underpinning those strategies is also presented (Table 1).

7.1 Soil acidification, greenhouse gas emission and crop productivity loss

Agricultural soil acidification occurs in intensive monoculture cropping systems[48]. Acidification alters soil biogeochemistry, soil fertility and soil health remarkably[48,49]. It is mostly caused by the use of ammonium-based fertilizers, export of produce (harvested stalks for milling and trash removed from the field), nitrate leaching and excessive accumulation of soil organic matter. In China, most of the sugarcane crop is overfertilized, particularly with N fertilizers, and this greatly contributes to acidification[48]. A large area of the sugarcane growing regions has a soil pH of < 4.5 resulting in toxic levels of manganese accumulation in the leaves[50]. Low soil pH and excessive accumulation of Mn in leaves adversely affect the uptake and translocation of many elements such as calcium, iron, magnesium and phosphorous and disrupts cellular and

Table 1 Major sugarcane agriculture and crop productivity issues currently faced by the Chinese sugarcane industry

Issues	Solutions and outcomes
Declining profitability	More productive cultivars and optimized superior cropping systems for each region. Accelerate mechanization at all stages of crop production including harvesting. Consolidate small farms for efficiency gains
Relatively slow technology innovation and adoption	Promote high-quality, high-impact scientific research and development. Increase innovation adoption capacity, which is currently quite limited. Establish dedicated technology innovation demonstration centers across sugarcane industry
Low rate of genetic gains through breeding	Target cane yield > 75 $t \cdot ha^{-1}$ for normal production areas, > 90 $t \cdot ha^{-1}$ for high-yielding regions, and sugar content > 14% through superior cultivars. Consolidate and modernize breeding programs to produce superior cultivars
The need for green and highly productive cropping system	Remove soil, location (e.g., hillslopes) and environmental constraints to transform sugarcane cropping systems into a modern, highly efficient and productive cropping system through technological innovations. Promote green agricultural development by reducing the use of agrichemicals, improving soil health and soil fertility, and eliminating plastic film mulching. Accelerate the adoption of new crop production technologies.
Widespread incidence of diseases and pests	Reduce the incidence of pest and pathogens through resistant cultivars. Promote the use of clean planting material, and improve and implement strict quarantine procedures
Slow mechanization	Public-private-partnership to develop machineries suited for sugarcane crops and differing topologies (e.g., hill slope cultivation)
Talent training to increase the sugarcane industry research, development and management capacity	Develop sugarcane agriculture-specific courses and training workshops, identify and train future leaders to strengthen research and development capacity

physiologic processes such as chlorophyll production, photosynthesis, controlling oxidative stress[51]. All these effects of acidification are reported in sugarcane grown in acid soil[50,52]. Over the last decade, soil acidification has become so severe that up to 40% of Guangxi sugarcane production area experiences some level of ratoon crop chlorosis and yield loss (Fig. 1)

Export of base cations is also a contributor of soil acidity in sugarcane soils. For example, 100 t of harvested cane exports about 150 kg K and 20 kg each of Ca and Mg are exported every year. Thus, loss of nutrients through this process must be factored into balanced farm nutrition programs. Soil acidity affects soil microbiome and soil biology[53], which in turn influences mineralization and nutrient cycling. Hence, managing soil acidity is important for soil health and to realize maximum crop productivity.

Fig. 1 Chlorotic ratoon sugarcane in Guigang, Guangxi.

Reversing soil acidification and maintaining soil pH within a favorable range for plant nutrient uptake is a key requirement of sustainable and economic sugarcane production. Reducing N fertilizer input is the first and foremost step needed to reverse soil acidification in Chinese sugarcane production system. With NPK application rates used by farmers range from 750 to 1300, 150 to 300, and 250 to 500 $kg \cdot ha^{-1}$, respectively, so there is substantial scope for controlling acidification just by reducing fertilizer input alone. Concurrently, liming and increasing soil organic matter further help reverse soil acidification, and improve soil biology and soil health[54].

Reducing fertilizer input, optimized nutrition, liming and preserving healthy soil are important measures needed to regain and sustain fertile and healthy soil. Also, such measures have large ecological benefits. For example, sugarcane cultivation is a significant source of GHGs and reducing fertilizers, particularly N fertilizers, will have large positive impacts on reducing GHG emissions[7]. Also, an added element in the nutrition context is exploiting enhanced-efficiency fertilizer technologies for delivering nutrients to match crop demand[55]. This will further help reduce fertilizer use and GHG emissions, making Chinese sugarcane production more green and environmentally sustainable.

7.2 Heterogeneity of farming landscape topography, regional climate, and spatial configuration of planting

In China, sugarcane cultivation on hillslopes is common with the majority of the crop is produced by smallholder farms in this way, with a multitude of spatial configuration for cropping practiced. Hillslope topography accelerates soil erosion and nutrient loss through runoff. The heterogeneity of spatial arrangement of crops in smallholder farms further aggravates soil and nutrient loss[56]. While studies have shown that consolidating smallholdings into larger ones will increase resource use efficiency and productivity and reduce fertilizer use[57], the environmental and ecological benefits from reduced fertilizer and other agrochemical use can be negated by accelerated erosion and runoff due to increase in slope length[57]. However, soil erosion and runoff, and thus nutrient loss from sugarcane crops on hillslopes, can be greatly reduced without yield loss by changing the current planting pattern by distributing the new planting to different positions covering 30% of the cultivated area of hillslopes[57]. Most of the research on sugarcane cropping system is conducted on flat lands and the recommendations from those studies have little or limited bearing on hillslope cultivation. This is further complicated by the large climatic (from tropics to subtropics with freezing temperature) and geographical (flat low-lying land to steep hillslopes) variation that exists across sugarcane production regions in China[29,30]. Optimizing crop spatial configuration to suit different regions should be a priority to achieve sustainable sugarcane production.

7.3 Soil biology, soil organic matter, crop rotation and soil health nexus

Understanding of soil physical and chemical properties is well advanced on knowledge on soil biology remains limited. In general, soil microorganisms and other soil organisms provide a number of ecosystem services such as decomposition of organic matter, soil formation, nutrient cycling and storage, provision of nutrients for plant uptake and suppression of pests and diseases[58]. Land use change from native vegetation to crop production greatly impacts on the soil microbial community. For example, conversion of forest land to sugarcane soil reduced soil microbial population by 50%–70%[59]. Also, continuous sugarcane cropping resulted in significant changes in soil physicochemical properties and the soil bacterial and fungal community composition[53]. A number of studies in various crops including sugarcane show that mineral N application increases diversity and amount of soil bacteria and adversely affects fungal community[60]. Clearly, these findings suggest the importance of preserving soil biology for sustainable sugarcane cropping.

In China, sugarcane crops are fertilized with excessive amounts of mineral N fertilizers with substantial negative impact on soil biology[53]. Given the fact that even in well-managed sugarcane cropping systems only about 30% of mineral N applied is used by the crop, the bulk of the N needed for the crop is supplied by mineralization of soil organic matter[36]. Unfortunately, Chinese sugarcane soils have a relatively low soil organic matter content. Therefore, strategies to increase soil organic matter should be part of the N management for sustainable sugarcane cropping. This includes retention and incorporation of cane trash into soil, crop rotation, intercropping, and application organic amendments such as mill waste (e.g., bagasse, mill filter cake and vinasse).

Using an organic N in place of mineral N for sugarcane production has several ecological benefits as well. Although, retaining and incorporating trash in the soil after harvest may have little immediate benefit as a source of N, it facilitates soil organic matter accumulation which in turn becomes a significant stock of nutrients for successive crops[36]. Legumes as a rotation crop can provide an effective source of organic matter and N for sugarcane[61]. A soybean crop (with grains retained) yielding 6 $t \cdot ha^{-1}$ DW provides up to 270 $kg \cdot ha^{-1}$ N for the successive sugarcane crop. Legume intercropping is also a useful approach in supplying N and soil organic matter but found to be less effective than when grown as rotation crops.

The advantage of incorporating legume rotation crop is manifold. Besides being an excellent source of N and biomass, it reduces pathogen buildup, improves soil biology and soil health. This has been proven in many crops including sugarcane[61]. Thus, legume rotation comes with considerable economic and environmental benefits, and it must be included as a component of sustaining sugarcane cropping system. Unfortunately, adoption of rotation crop is very limited in sugarcane agriculture despite obvious and substantial benefits.

7.4 Tackling the water limitation- recurring drought, plastic film mulching and limited advances in genetics

Water limitation, particularly at the planting time and the active crop growth stage, is a major constraint of crop productivity and a significant cause of yield gap industry-wide.

Unfortunately, there is no substitute for water as far as crop production is concerned. Also, recurring drought is a feature of the regional climate where sugarcane is grown in China; hence it must be managed. Plastic mulching of planted rows is widely practiced to conserve water for initial shoot development with remarkable positive outcomes[28]. However, its sustainability is highly questionable. Plastic pollution of water, soil and air in China and elsewhere is now well recognized[62]. Biodegradable plastic could be an option as it can be readily made; however, it is uneconomical for large-scale agricultural use. Use of water-absorbing soil additives is also not cost-effective for broadacre agricultural application. The limited water management option left is to maximize the use of stored soil moisture by optimizing planting time and strategic supplementary irrigation, where an opportunity exits. Previous efforts to improve water stress tolerance through genetic approach did not yield much benefits in sugarcane[5]. However, a targeted introgression of locally adapted *Saccharum spontaneum* appears to be an option to improve water stress tolerance of cultivars.

7.5 Provision of clean sett (planting material)

Establishing and maintaining a healthy crop starts with planting clean sett. This is important to prevent pests and diseases passing on from one crop to another. In many sugarcane growing countries, commercial companies supply clean sett to growers. In China, this aspect of sugarcane production is well recognized and considerable effort is now underway to supply clean sett[34]. However, the current capacity of clean seedcane supply is limited. Transitioning the entire sugarcane industry to planting clean sett would raise the crop productivity considerably. This would also help reduce pests and diseases burden currently experienced by the sugarcane industry.

8 RESEARCH AND DEVELOPMENT TARGETS FOR SUSTAINABLE SUGARCANE CROP PRODUCTION SYSTEM

The full potential of superior sugarcane cultivars can only be realized if they are allowed to express their full growth potential. So, identifying the most suitable growing system for each region that can be used for commercial crop production is extremely important to get maximum economic value of superior cultivars for farmers and milling companies. Given the soil and climatic variability across different sugarcane production regions in China, the components of an optimal cropping system vary between regions, including cultivars. The research and development targets described below are to remove crop productivity and sustainability barriers and help develop a green, economic and environmentally sustainable sugarcane cropping system in China.

(a) Develop a cropping system with minimum strategic tilling.
(b) Reduce fertilizer use to improve soil fertility.
(c) Use the most appropriate nutrient formulations and products to minimize nutrient supply and demand mismatch and nutrient loss.
(d) Provision and maximum adoption of pest and pathogen-free planting material in all regions.
(e) Improve soil biology to sustain soil fertility.
(f) Identify and encourage the most appropriate intercropping system to improve and maintain soil fertility.
(g) Encourage fallow with or without break crop to control soilborne pests and pathogens, and increase soil fertility/soil health.
(h) Replace plastic film with biodegradable film for crop production.
(i) Select matching cultivars for each region and cropping system.
(j) Improve the quality and reduce the quantity of planting material for new planting.
(k) Promote precision agriculture technologies.
(l) Develop crop modeling capacity.
(m) Accelerated adoption of machine harvesting.
(n) Establish a highly-effective agriculture extension network throughout the industry.

9 CONCLUSIONS

Sugarcane is a strategic crop in China with considerable socioeconomic significance. Demand for sugar in China is growing and its annual consumption is projected to reach 16.4 Mt by 2030. China imports 4–5 Mt of sugar annually and is expected to remain high at least for a decade. Sugarcane accounts for 85%–90% of the sugar produced locally. Sugarcane crop productivity in China is relatively low compared to many other countries, and significant improvement in both cultivar development and cropping system is required to make the sugarcane industry cost-competitive. Chinese sugarcane production is not only a high-cost, low-profit enterprise, but also environmentally challenging. Long periods of monoculture with excessive mineral fertilizer use, especially N fertilizer, render sugarcane soils across the growing area acidic, with relatively low organic matter and soil fertility. The extent of soil pathogen and pest infestation remains unclear. Declining profit margin, low crop productivity, soil degradation and environmental cost call for major cropping system innovations to make sugarcane production economically and environmentally sustainable. Effective measures to reverse soil acidification such as liming, regaining soil biology and fertility through legume rotation with six-month fallow prior to rotation crop, and intercropping where feasible. Legume fallow rotation will provide multiple benefits such as provision of organic matter and nutrients, especially N, reduced reliance on mineral fertilizers and control of soilborne diseases and pests. Use of organic amendment such as mill waster products, manure and compost will rapidly replenish nutrients and improves soil health. To complement these biological solutions, judicious use of new-generation fertilizers such as enhanced-efficiency fertilizers to supply nutrients to match crop demand will greatly reduce chemical farm inputs, GHG emissions and increase crop productivity. Use of biodegradable plastic films and clean sett for planting, reduced/strategic tilling, retention and incorporation of trash back into soil, and wider adoption of machine harvesting will further strengthen the sustainability of sugarcane cropping system and make them more environmentally benign. Ultimately, the extent of adoption of the measures given above will determine the transition of current sugarcane farming practices into a green, ecologically-balanced and economically viable crop production system.

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Compliance with ethics guidelines

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