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RESEARCH ARTICLE

Identification of Appropriate Agri-technologies Minimizing Yield Gaps in Different Sugarcane-Growing States of India

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Abstract In India, five states, viz., Uttar Pradesh, Maharashtra, Karnataka, Tamil Nadu and Bihar, contribute about 84.64% sugarcane production of the country and occupy about 82.46% cropped area. The mean productivity of these states is also higher as compared to remaining states. However, the yield gap up to 33.0 t ha^{-1} prevails among these states. The performance of technologies in different states also varies depending on constrains and potentials of the region. Thus, the objectives of our study were (1) to assess the yield gap between attainable yield and farmers yield in potential sugarcane-growing states of the country and (2) to determine the long-term relationship between improved technologies and sugarcane yields at various levels. Yield gap analysis revealed that Uttar Pradesh recorded the highest positive correlation between period and sugarcane yield ($R^2 = 0.917/r = 0.96$) and showed that technological advancements caused linear increase in sugarcane yield. Out of eight technologies, five technologies, i.e. improved variety, pit method of planting, intercropping, drip irrigation and ratoon management, enhanced sugarcane yield by > 20% and could be placed as top rankers. In Maharashtra, improved variety, ratoon management, intercropping and integrated nutrient management were recorded as top rankers and improved sugarcane yields in the range of 20.44–31.29%, individually. In Karnataka, drip irrigation, intercropping, ratoon management and improved varieties increased > 20% sugarcane yield as compared to state average sugarcane yield. However, wide row spacing and INM could increase yield level in the range of 15.17% and 17.65%, respectively. In Tamil Nadu, the various technologies could increase about 4.35–35.87% higher sugarcane yields as compared to farmers practice. Pit method planting showed the highest improvement in yield (35.87%). Improved varieties, integrated weed management, intercropping and ratoon management showed positive effect in the range of 13.28–19.0% as compared to mean of technologies demonstrated in five states. In Bihar, the improved variety contributed 40.2% yield increase as compared to state average yield (59.25 t ha^{-1}). Ratoon management (35.14%) and intercropping in sugarcane (31.76%) could also be ranked in the top category in increasing sugarcane yields. Thus, it could be recorded that improved variety in Maharashtra and Bihar, pit/trench method of planting in Uttar Pradesh and Tamil Nadu drip irrigation and ratoon management in Karnataka are the major technologies contributing in sugarcane yield. Therefore, these technologies need to be promoted in the potential sugarcane-growing states to improve the national average.

Keywords Pit/trench planting · Improved varieties · Yield gap · On farm demonstration · Integrated nutrient management · Ratoon management

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Introduction

In India, sugarcane (*Sachharum officinarum*) is grown in an area of 4.73 M ha with a production of 376.9 MT at an average yield of 79.65 t ha^{-1} (DAC 2018). Recent improvements in sugarcane productivity are evidences of technological advancements such as developing improved varieties, crop production and protection technologies and their dissemination and adoption on farmers' fields through effective linkages among various research and development agencies. In India, five sugarcane-growing states (Uttar Pradesh, Maharashtra, Karnataka, Tamil Nadu and Bihar) occupy more than 82% area of sugarcane crop and contribute about 85% sugarcane production in the country (Table 1) (DAC 2018). However, the difference in sugarcane productivity up to 33 t ha^{-1} among these states exists, indicating scope of further improvement. Uttar Pradesh and Maharashtra contribute more than 69% sugarcane production in the country and occupy about 56% sugarcane area at the national level (DAC 2018).

The achievable possible yield for sugarcane is about 280 tonnes per ha per year, and an experimental plots in Brazil have demonstrated yields of 236–280 tonnes of cane per ha (Bogden 1977). In several cases, sugarcane yield of 250–300 t ha^{-1} on fields of progressive farmers in tropical state like Maharashtra has also been recorded (Katoch 2017). However, selection of variety, availability of irrigation water, plant population management, tillage practices, and nutrient and weed management strategies are the key components in improving the sugarcane productivity beyond 200 t ha^{-1} (Katoch 2017).

The sugarcane yield could be increased through adoption of improved varieties developed for the region (Ram et al. 2017). The genetic makeup of crop/variety governs the physiological and biochemical enhancements in biomass accumulation for improving quantitative (yield) as well as qualitative (sugar content) traits. Sugarcane is deep rooted crop, and more than 75% roots are concentrated within 45–50 cm soil depth (Agrigoa expert 2020). Deep tillage/subsoiling pulverizes soil up to 30–45 cm depth and improves rhizospheric environment for better crop growth which resulted in improved sugarcane and sugar yields (Shukla et al. 2018a). Thus in most of the cases, pit/trench method of planting also improved sugarcane yield (Yadav and Kumar 2005). Organics play an important role in optimizing nutrients supply to crop. However, improvement in soil tilth (physical) and microbial population is another most important factors affecting crop growth and yields (Shukla et al. 2015). Integrated nutrient management provides nutrients in adequate amount and balanced proportion keeping in view the demand of crop and resulted in sugarcane yield improvement (Shukla et al. 2013a, 2015). Integrated weed management (IWM) resulted in sugarcane yield at par with manual hoeings. However, the practice of IWM saved man days and has been found economically viable (Chauhan et al. 1994). Intercropping of mustard, potato, French bean, pea, gram, wheat with autumn/winter planted sugarcane increased land use efficiency and has been found remunerative. Besides, intercropping of green gram, black gram and cow pea has also been found beneficial with spring sugarcane in subtropical region of the country (Shukla et al. 2017a). The intercropping with sugarcane facilitates midseason income generation to farmers, so they can manage long-duration crop in better way through timely procurement of market purchased inputs. Integrated pest management has been found effective against any single measure adopted for managing insect-pest in sugarcane (Naidu 2009). Drip irrigation saved more than 40% irrigation water and improved sugarcane yield at several locations in subtropical and tropical regions of the country (Shukla et al. 2019). Ratoon is an essential component of sugarcane agriculture, and profitability of sugarcane farming depends on the practice of multiratooning (Shukla et al. 2008, 2018a). It reduces the cost of production through seed saving, initial field preparation, planting operation and facilitates early crushing.

These crop management strategies play a significant role in improving sugarcane yields. The performance of various technologies and benefits derived from each technology may be different due to physical, chemical and biological constraints faced by sugarcane growers at various places as per our hypothesis. Thus, the performance of technology could vary depending on constrains of the region, and the realizable potential yields could be obtained only by integration of viable technologies with recommended package of practices. Thus, the objectives of our study were (1) to assess the yield gap between attainable yield and farmers yield in potential sugarcane-growing states of the country

Table 1 List of centres and prominent sugarcane varieties

State	Location of different centres	Sugarcane varieties adopted in various states for demonstration during the period
Uttar Pradesh	Lucknow, Shahjahanpur, Seorahi, Muzaffarnagar and Gorakhpur	Co 0238, CoS 767, CoS 8436, CoJ 64
Maharashtra	Rahuri, Kolhapur, Pune, Pravaranagar, Parbhani	Co 86032, CoM 0265, Co 92005, CoC 671, Co 94012
Tamil Nadu	Coimbatore, Cuddalore, Pugalur	Co 86032, CoC (Sc) 24, CoV 09356, TNAU Si(Sc) 7, CoSi 6
Karnataka	Mandya, Sakshwar, Dharwad	Co 86032, CoM 0265, CoSnk 03632, SNK 07680, CoC 671
Bihar	Pusa, Motipur	BO 91, BO 110, CoP 9301, CoP 2061, BO 153

and (2) to determine the long-term relationship between improved technologies and their effects on sugarcane yields (farmers yield, state average yield and national average yield) and (3) to suggest prominent technologies for improving sugarcane productivity in various states/country.

Materials and Methods

Frontline demonstrations during 2004–2005 to 2016–2017 on various technologies were conducted in five sugarcane-growing states, viz., Uttar Pradesh, Maharashtra, Karnataka, Tamil Nadu and Bihar. In these states, each production technology was demonstrated on one ha area. Ten farmers were selected for implementation of a single technology. Thus mean of ten farmers for each technology was worked out. Ten technologies were demonstrated in Tamil Nadu, followed by eight in Uttar Pradesh, seven each in Maharashtra and Karnataka and four in Bihar keeping in view the relevance of that technology in a particular state. A list of centres in different sugarcane-growing states and varieties adopted during the period is given in Table 1. In addition to, the details of technology demonstrated in five sugarcane-growing states with conventional practice have also been given. Demonstrations were conducted on farmers' fields in radius of 30–50 km of each centre. Percent deviation in rainfall pattern in various states has also been presented in Fig. 1.

Recommended package of practices for growing of sugarcane crop in the region was adopted except the treatment (technology applied) on farmers' fields. Standard deviation of each technology demonstrated in different states was worked out to analyse the significant differences. The mean of ten farmers of each technology was worked out and statistically analysed to determine the significant variations. The performance of various technologies in different states was compared with state average yield and also with the mean performance of particular technology in five states. After that integrated performance of all demonstrated technologies for 13 years was also compared with average yields of states and country. The improved technologies were demonstrated on farmers' fields during 2004–2005 to 2016–2017. The contribution of each technology in increasing sugarcane yields in each state was determined to derive the conclusion on potential of technology in improving sugarcane yield. The ranking was also given on the basis of yields improvement through particular technology on farmers' fields as compared to state average yield of sugarcane (0–10% yield improvement—average; 10–20% yield improvement—good; and > 20% yield improvement—very good).

Generally five categories of crop yields have been considered in yield gap analysis, i.e. theoretical yield, potential yield, water-limited yield, attainable yield and actual yields (FAO 2015). Attainable yield is the best yield obtained through application of all technological advancements in a particular ecosystem (Hall et al. 2013). However, the actual yield reflects the current state of soils and climate, skill of farmers and their average use of technology. The difference between two levels of yields (attainable yield and actual yield) has been considered 'Yield Gap'. Frontline demonstrations on different technologies were executed under the supervision of scientists of SAUs/Agricultural Experiment Stations/ICAR Institutes. State average yield represents the mean performance of farmers' practices on larger area and represents farmers' yields. Thus, our study was focused on gap of attainable yield and actual yield which is being discussed in the current paper.

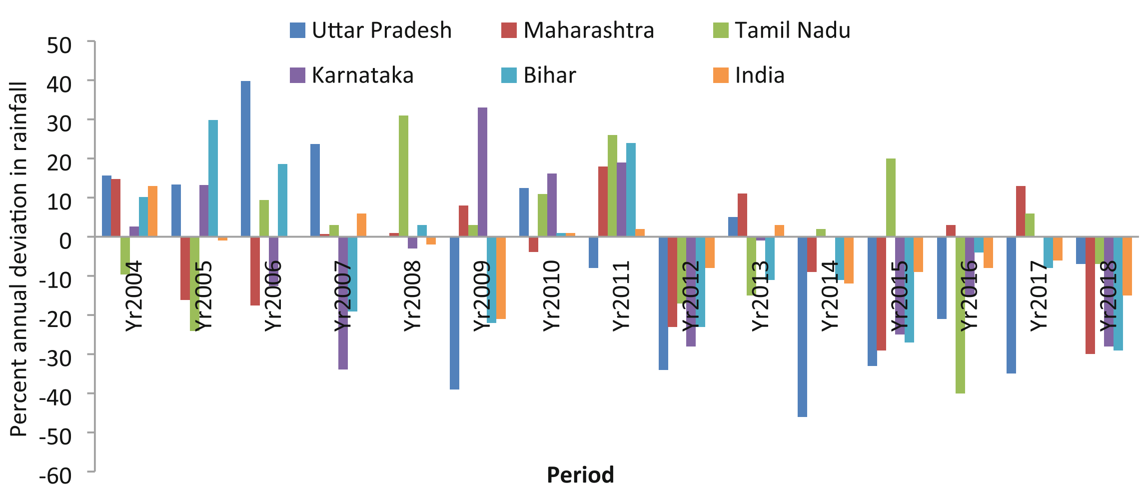

Fig. 1 Per cent deviation in annual rainfall during 2004–2018 in different states of the country

Table 2 Contribution of top five states in sugarcane area and production in India

State	Area (m ha)	Percentage area of the whole country	Production (million tonnes)	Percentage of whole country	Sugarcane yield (t/ha)
Uttar Pradesh	2.23	47.21	177.06	46.98	79.25
Maharashtra	0.90	19.06	83.13	22.06	92.16
Karnataka	0.35	7.40	28.26	7.50	80.75
Tamil Nadu	0.18	3.80	16.54	4.39	92.00
Bihar	0.24	4.99	13.98	3.71	59.25
Total (five states)	3.9	82.46	318.97	84.64	81.78
Total (country)	4.73	100	376.9	100	79.65

Source: DAC (2018)

Table 3 Impact of technology adoption on sugarcane yield in India

State	State farmers practices average yield (t/ha)	Field-demonstrated trials average yield (t/ha)	Net gain yield (t/ha)	% Increased yield (t/ha)
Uttar Pradesh	79.25	96.10	16.88	21.30
Maharashtra	92.16	111.4	19.24	20.87
Karnataka	80.75	98.57	17.82	22.06
Tamil Nadu	92.00	112.9	20.9	22.71
Bihar	59.25	77.05	17.85	30.15
SD (±)	13.45	14.47	–	
CV (%)	16.67	14.58	–	

Results

Sugarcane Yields at the National Level

In India, five states, viz., Uttar Pradesh, Maharashtra, Karnataka, Tamil Nadu and Bihar, contributed about 84.64% sugarcane production (Table 2) of the country and covered about 82.46% cropped area. The mean productivity (81.78 t ha^{-1}) of these states was also higher as compared to remaining states. However, the yield gap of up to 33.0 t ha^{-1} prevailed among these states. Production in subtropical region had lower average yield (59.25 t ha^{-1} in Bihar) *vis-a-vis* Maharashtra (92.16 t ha^{-1}) and Tamil Nadu (92.0 t ha^{-1}) belonging to tropical region. However, Uttar Pradesh belonging to subtropical region showed 33.86% higher average yield of sugarcane (79.25 t ha^{-1}) than Bihar. Thus, Bihar and Uttar Pradesh are potential states in increasing achievable potential of sugarcane in subtropical region. However in Karnataka, Tamil Nadu and Maharashtra states, sugarcane productivity ranged from 80.75 to 92.16 t ha^{-1} (Table 3). However, keeping in view the performance of advanced technologies, we could also improve crop yields in these states ranging from 77.05 to 112.9 t ha^{-1}.

Sugarcane Yield at State Level

Sugarcane productivity in various states ranged from 59.25 t ha^{-1} (Bihar) to 92.16 t ha^{-1} (Maharashtra—Table 3). However, various technologies demonstrated in these states showed mean yield increase of 16.88–20.9 t ha^{-1} which resulted in an improvement of 20.87–30.15% over the state average yield (Table 3). Thus, technology development and dissemination hold great promise in all these sugarcane-growing states. However, the degree of improvement varied significantly in different states. The net increase in sugarcane yield (17.82–20.9 t ha^{-1}) in tropical states (Maharashtra, Karnataka and Tamil Nadu) was also recorded higher than Uttar Pradesh (16.88 t ha^{-1}) and Bihar (17.85 t ha^{-1}). However, the mean per cent increase (30.15%) was the highest in Bihar as compared to other states. This signalled scope of greater improvement in crop yields after following improved technologies in subtropical region.

1. *Uttar Pradesh*

The various technologies could produce sugarcane yield ranging from 84.0 to 114 t ha^{-1} in Uttar Pradesh (Table 4). Adoption of improved variety could increase 27.44% higher yield than state average yield (79.25 t ha^{-1}). However, the increase was negative, if compared with mean of five states (105.4 t ha^{-1}). Pit method of planting increased 43.85% sugarcane yield and showed that the technology on farmers fields could significantly increase yield up to 114 t ha^{-1}. However, it yielded 4.6% lower in comparison with mean of five states (119.5 t ha^{-1}). However, this difference was found nonsignificant. Integrated nutrient management (INM) could increase yield by 8.52% over the state average yield. However, the integrated weed management (IWM) could increase sugarcane yield by 6.67% over state average yield (79.25 t ha^{-1}). Intercropping in sugarcane could increase cane equivalent yield (sugarcane yield and component crop yields in terms of sugarcane) by 27.44% over state average yield (79.25 t ha^{-1}). Integrated pest management (IPM) could prove its effectiveness and increased yield by 13.56% during the period of 2004–2005 to 2016–2017 (Fig. 2). Drip irrigation and ratoon management could increase sugarcane yield by 21% over state average yield. Overall in Uttar Pradesh, all the demonstrated technologies on farmers' fields produced higher yields by 5.99–43.85% as compared to farmers practice (state average yield). However, in comparison with mean of five states, no technology could reach to that level. Thus we could still find higher scope of increasing sugarcane yield in state.

Demonstration plot yields along with state and national average during 2004–2005 to 2016–2017, and regression lines have been depicted (Fig. 2). Mean state average sugarcane yield of Uttar Pradesh during the period indicated positive correlation ($R^2 = 0.462/r = 0.68$) and regression equation, i.e. Y (sugarcane yield) = 1.02(year) + 53.57, was worked out. Thus during the period, a linear equation showed positive increase in increasing sugarcane yield. This could be possible through technological advancements and their translation on farmers fields as well. However, the national average showed higher value ($R^2 = 0.486/r = 0.69$). The demonstration plots in Uttar Pradesh recorded the highest positive correlation between period and sugarcane yield ($R^2 = 0.917/r = 0.96$) and showed that technological advancements caused linear increase in sugarcane yield. Linear equation, i.e. $Y = 0.895x + 89.95$, indicated close association of observed and expected values of sugarcane yields during 13-year period in Uttar Pradesh (Fig. 2). Out of eight technologies evaluated during 2004–2016–2017, five technologies (improved variety, pit method of planting, intercropping, drip irrigation and ratoon management) yielded > 20% and could be placed as top rankers (very good). Integrated pest management could be placed as middle ranker (10–20%—good), and INM and IWM were categorized as average ranker (< 10% increase in yield) on the basis of performance of technologies on farmers' fields.

2. *Maharashtra*

Various technologies demonstrated in Maharashtra state yielded sugarcane in the range of 101–121t ha^{-1} (Table 4) over the 13-year period during 2004–2005 to 2016–2017. The per cent increase in yield over the state average yield was 8.51% (with adoption of biofertilizer) to 31.29% (with adoption of improved variety). Adoption of improvement

Table 4 Sugarcane yield on demonstration plots (t ha^{-1}) in top five states of the country

Technology adopted	Abb.	Uttar Pradesh	Maharashtra	Karnataka	Tamil Nadu	Bihar	Mean yield (t/ha)	SD (±)	CV (%)
Improved variety	IV	101	121	102	123	80	105.40	7.69	6.74
Pit/trench method of planting	PMP	114	NC	NC	125	NC	119.50	9.32	7.36
Biofertilizer	BIO	NC	100	87	103	NC	96.67	7.36	5.49
Wide row spacing	WRS	NC	NC	95	114	NC	104.50	7.13	5.33
Integrated nutrient management	INM	86	111	93	109	NC	99.75	7.00	5.99
Integrated weed management	IWM	84	101	NC	105	70	90.00	6.98	6.21
Intercropping in sugarcane	IIS	101	117	104	125	78.2	105.04	8.95	7.73
Integrated pest management	IPM	90	NC	NC	96	NC	93.00	5.20	5.76
Drip irrigation	DI	97	112	107	113	NC	107.25	8.83	6.87
Ratoon management	RM	96	118	102	116	80	102.40	6.40	5.27
Mean		96.13	111.43	98.57	112.90	77.05	99.22		
SD (±)		9.67	8.22	7.09	9.81	5.56	9.10		
CV (%)		10.06	7.38	7.19	8.69	7.15	9.17		

NC not conducted

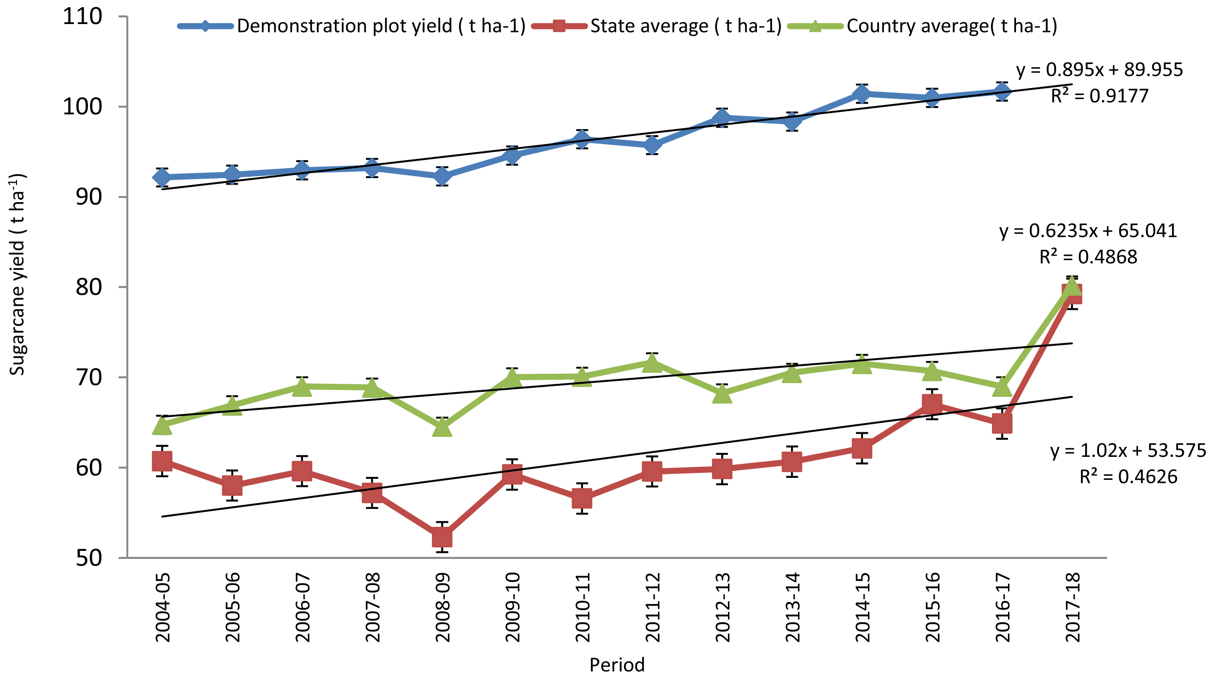

Fig. 2 Relationship between period and sugarcane yields in Uttar Pradesh

varieties brought forth yield to the level of 121 t ha^{-1}. Integrated weed management (IWM) could result in 9.59% higher yield in demonstration plots (101 t ha^{-1}) over the state average yield (92.16 t ha^{-1}). Intercropping could produce 26.95% higher cane equivalent yield over the state average sugarcane yield. Drip irrigation could also improve sugarcane yield by 21.53%. However, the ratoon management could improve yield by 28% over the state average yield (92.16 t ha^{-1}). Thus improved variety, ratoon management, intercropping and INM were recorded as top ranked technologies and improved sugarcane yields in the range of 20.44–31.29%, individually. Integrated weed management and biofertilizer application could improve sugarcane yield $<$ 10% over state average yield of sugarcane and was recorded as average ranker in Maharashtra.

In Maharashtra state, all the demonstrated technologies also reflected superiority in mean of demonstrations in five states. Adoption of improved variety, INM, IWM, intercropping in sugarcane and ratoon management showed $>$ 10% improvement over the mean of five states. Performance of various technological advancements during the 13-year period in Maharashtra state indicated the positive correlation between period and yield ($R^2 = 0.318/r = 0.56$—Fig. 3). However, the Maharashtra state during 13-year period suffered several ups and downs in sugarcane yields (Fig. 3) because of erratic distribution of rainfall (DAC 2004, 2018; Fig. 1) which affected degree of relationship. However, the regression equation ($Y = 2.273x + 96.05$; $R^2 = 0.862/r = 0.98$) of front-line demonstration trials showed positivity as compared to state equation ($Y = 1.020x + 70.30$; $R^2 = 0.318/r = 0.563$). Higher number of drops during 2005, 2006, 2012 and 2015 in state average sugarcane yields was recorded due to decline in mean annual rainfall (Fig. 1).

3. *Karnataka*

Adoption of improved variety could increase the mean sugarcane yield up to 102 t ha^{-1} and recorded an increase of 26.32% (Table 4) as compared to state average yield (80.75 t ha^{-1}). However, drip irrigation had shown the highest sugarcane yield (107 t ha^{-1}) and increased sugarcane yield by 32.51% as compared to state average yield. Intercropping in sugarcane could improve cane equivalent yield by 28.79% over the sole sugarcane yield. Thus four technologies, viz., drip irrigation, intercropping, ratoon management and improved varieties, were recorded as top rankers and increased $>$ 20% sugarcane yield as compared to state average. However, wide row spacing (WRS) and INM were considered as good and could increase yield level in the range of 15.17% and 17.65%, respectively. Biofertilizer could improve 7.74% sugarcane yield; however, due to cost-effective operation, technology holds great promise for sustaining soil fertility and crop productivity in Karnataka.

In Karnataka, all the technologies could not exceed mean cane yield of five states. However, three

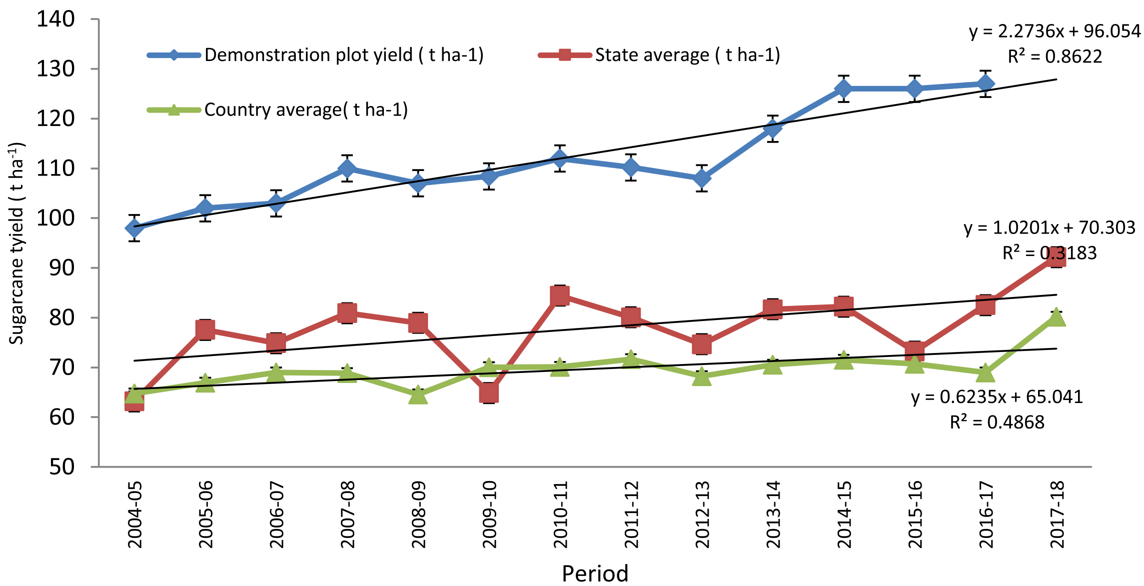

Fig. 3 Relationship between period and sugarcane yields in Maharashtra

technologies, viz., intercropping, ratoon management and drip irrigation, produced sugarcane yields at par with five states of average sugarcane yield. Adoption of improved variety in Karnataka also resulted in statistically at par yield (102 t ha^{-1}) as compared to mean of five states (105.4 t ha^{-1}). Biofertilizer application and wide row spacing could not reach to the level of mean of five states (Table 4). Water is a key component and drip irrigation produced the highest sugarcane yield (107 t ha^{-1}) and is comparable with improved variety in Karnataka. Intercropping also holds great promise, and keeping in view the increasing productivity and profitability of sugarcane in Karnataka, the practice could be adopted on large scale. Ratoon management and improved varieties individually could increase the sugarcane yield up to 102 t ha^{-1} and showed greater scope in future for increasing sugarcane yield in Karnataka.

In Karnataka also, the several ups and downs in sugarcane productivity during 13-year period were received. During 2007, 2012 and 2015–2017, deficit rainfall was received (> 20% deficit from long period average—Fig. 1). Despite positive correlation between period and state average sugarcane yield was maintained with regression equation ($Y = 0.321x + 87.50$—Fig. 4). However, linear relationship between period and sugarcane yield was weakened ($R^2 = 0.047/r = 0.216$). However, in demonstration plots, the regression equation ($Y = 0.954x + 91.89$; $R^2 = 0.593/r = 0.77$) showed that sugarcane yield could be sustained through adoption of improved technologies. The reduction in annual rainfall caused a significant reduction in state average sugarcane yield (Fig. 4). However, in the demonstration plots, the yield could be maintained in the range of 87–107 t ha^{-1}.

4. *Tamil Nadu*

In Tamil Nadu, the various technologies could yield 4.35–35.87% higher sugarcane yields as compared to farmers practice in the region (Table 4). However, the mean sugarcane yield obtained due to implementation of various technologies was recorded as 96–125 t ha^{-1}. Pit/trench method of planting showed the highest improvement in yield (35.87%) as compared to state average yield (92 t ha^{-1}). However, it was found at par with intercropping in sugarcane. Improved variety could increase mean cane yield level up to 33.7%. The differences with pit/trench method of planting and intercropping were statistically nonsignificant. Drip irrigation, wide row spacing and ratoon management increased sugarcane yields in the range of 22–26% as compared to state average sugarcane yield. However, INM and IWM could increase yield about 14–18%. Biofertilizer also increased sugarcane yield beyond 10%. Keeping in view the minimal cost of technology, the application of biofertilizers (*Gluconacetobacter diazotrophicus, Azotobacter, Azospirillum* and phosphate-solubilizing bacteria, especially *Pseudomonas* and *Bacillus spp*) could be found useful (Shukla et al. 2018b).

In Tamil Nadu, all the technologies showed positive impact as compared to mean of five states. The four technologies, viz., improved varieties, IWM, intercropping and ratoon management, showed positive effect in the range of 13.28–19.0% as compared to mean of

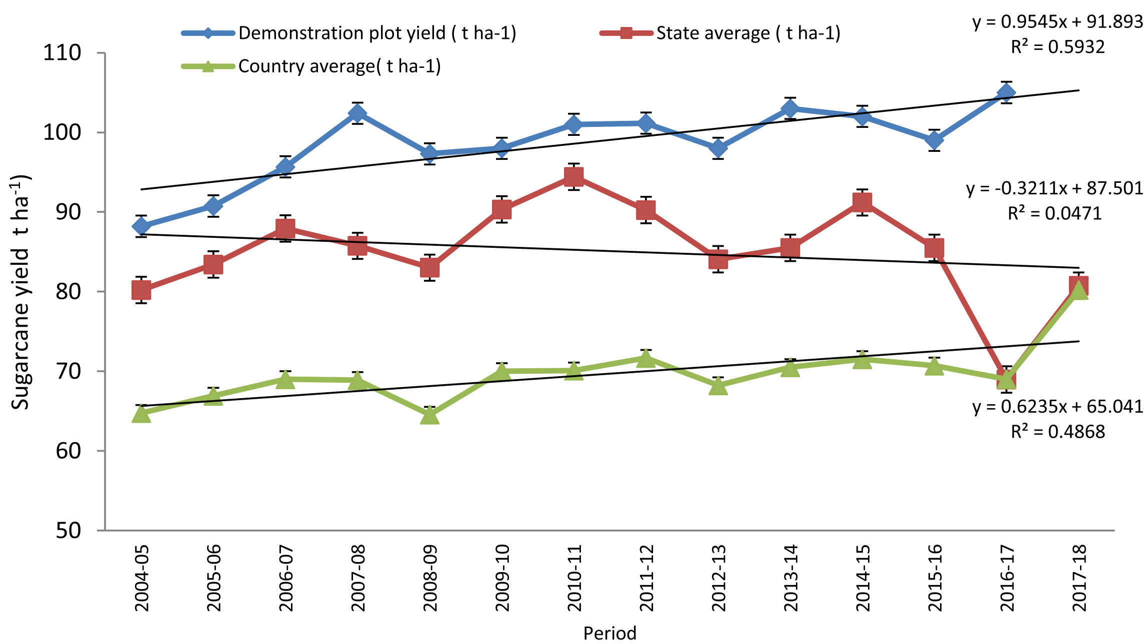

Fig. 4 Relationship between period and sugarcane yields in Karnataka

technologies demonstrated in five states. Four technologies (biofertilizer, wide row spacing, INM and drip irrigation) showed 5–10% higher sugarcane yields as compared to mean of five states. Thus Tamil Nadu showed the highest contribution in all the technologies demonstrated and could be ranked first with respect to improvement in sugarcane productivity due to adoption of technology.

The highest fluctuations in sugarcane yield were recorded in Tamil Nadu. This affected degree of linearity of regression equation also (Fig. 5). Despite at state level, the positive correlation (R^2 = 0.356/r = 0.59) was maintained. Demonstration plots also showed lowest correlation (R^2 = 0.168/r = 0.41). Despite achieving higher

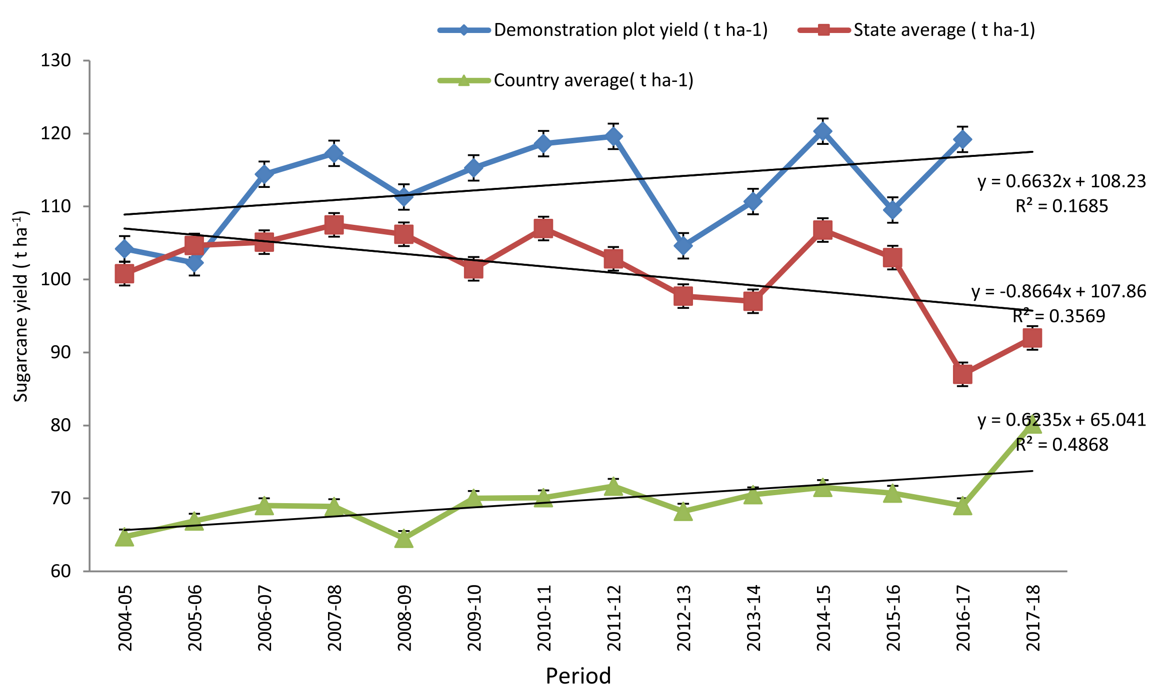

Fig. 5 Relationship between period and sugarcane yields in Tamil Nadu

Table 5 Details of technology demonstrated in various sugarcane-growing states of the country

Technology adopted	Uttar Pradesh	Maharashtra	Karnataka	Tamil Nadu	Bihar
Pit/trench method of planting	Centre-to-centre distance 120 cm depth of pit/trench is 30 cm, 6900 pits/ha	Centre-to-centre distance 120 cm depth of pit 30 cm, 6900 pits/ha	Centre-to-centre distance 120 cm depth of pit 30 cm, 6900 pits/ha	Centre-to-centre distance 120 cm depth of pit 30 cm, 6900 pits/ha	Centre-to-centre distance 120 cm depth of pit 30 cm, 6900 pits/ha
Conventional practice (CP)	Furrow planting	Furrow/trench planting	Furrow planting	Furrow planting	Furrow planting
Biofertilizer	*Gluconacetobacter diazotrophicus* (N fixer) and PSB (*Pseudomonas fluorescens*) CFU 10^{8-9} per gram culture.Liquid culture @ 1 L/ha	*Azotobacter (N fixer) diazotrophicus* and PSB (*Pseudomonas fluorescens*) CFU 10^{8-9} per gram culture.Liquid culture @ 1 L/ha	*Azotobacter (N fixer) diazotrophicus* and PSB (*Pseudomonas fluorescens*) CFU 10^{8-9} per gram culture.Liquid culture @ 1 L/ha	*Azotobacter (N fixer) diazotrophicus* and PSB (*Pseudomonas fluorescens*) CFU 10^{8-9} per gram culture.Liquid culture @ 1 L/ha	*Gluconacetobacter diazotrophicus* (N fixer)and PSB (*Pseudomonas fluorescens*) CFU 10^{8-9} per gram culture.Liquid culture @ 1 L/ha
Conventional practice (CP)	NPK through Chemical fertilizers	NPK through Chemical fertilizers	NPK through Chemical fertilizers	NPK through Chemical fertilizers	NPK through Chemical fertilizers
Wide row spacing	Single-row planting at 120 cm	Single-row planting at 150 cm	Single-row planting at 150 cm	Single-row planting at 150 cm	Single-row planting at 120 cm
Conventional practice (CP)	Single-row planting at 75/90 cm row spacing	Single-row planting at 90 cm row spacing	Single-row planting at 90 cm row spacing	Single-row planting at 90 cm row spacing	Single-row planting at 75/90 cm row spacing
Integrated nutrient management	Recommended N, P_2O_5 and K_2O 150, 60 and 60 kg/ha through inorganic fertilizers + 10 tonnes FYM/Press mud cake/ha	Recommended N, P_2O_5 and K_2O 250, 100 and 125 kg/ha through inorganic fertilizers + 10 tonnes FYM/Press mud cake/ ha	Recommended N, P_2O_5 and K_2O 250, 100 and 125 kg/ha through inorganic fertilizers + 10 tonnes FYM/Press mud cake/ha	Recommended N, P_2O_5 and K_2O 250, 100 and 125 kg/ha through inorganic fertilizers + 10 tonnes FYM/Press mud cake/ha	Recommended N, P_2O_5 and K_2O 150, 60 and 60 kg/ha through inorganic fertilizers + 10 tonnes FYM/Press mud cake/ha
Conventional practice (CP)	Recommended NPK as given above	Recommended NPK as given above	Recommended NPK as given above	Recommended NPK as given above	Recommended NPK as given above
Integrated weed management	Atrazin./@ 2 kg ai/ ha(PE) followed by 2, 4-D 1 kg ai/ha and one hoeing during maximum tillering stage	Atrazin./@ 2 kg ai/ ha(PE) followed by 2, 4-D 1 kg ai/ha and one hoeing during maximum tillering stage	Atrazin./@ 2 kg ai/ ha(PE) followed by 2, 4-D 1 kg ai/ha and one hoeing during maximum tillering stage	Atrazin./@ 2 kg ai/ ha(PE) followed by 2, 4-D 1 kg ai/ha and one hoeing during maximum tillering stage	Atrazin./@ 2 kg ai/ ha(PE) followed by 2, 4-D 1 kg ai/ha and one hoeing during maximum tillering stage
Conventional practice (CP)	Three manual hoeings	Three manual hoeings	Three manual hoeings	Three manual hoeings	Three manual hoeings
Intercropping in sugarcane	In autumn sugarcane: Mustard, potato, French bean, chick pea, pea, lentil: Spring cane: Mung bean, urd bean, cow pea	Seasonal planting: Summer groundnut, Soybean, Preseasonal: Potato, Gram, cabbage, Adsali: Groundnut, soybean, cowpea, radish, coriander, fenugreek	Maize, short duration legumes, oilseeds, vegetables, groundnut etc	Black gram, green gram, finger millet, soybean, groundnut	Mustard, potato, French bean, chick pea, pea, lentil with autumn planted sugarcane
Conventional practice (CP)	Sole planting	Sole planting	Sole planting	Sole planting	Sole planting

Table 5 continued

Technology adopted	Uttar Pradesh	Maharashtra	Karnataka	Tamil Nadu	Bihar
Integrated Pest management (for all states)	Management of Early shoot borer and Root borer				
	Cultural control				
	Deep summer ploughing; Inter culture and hand weeding; Timely irrigation; Light earthing-up of crops three months after planting; Grow onion/garlic/coriander as intercrop In ratoon crop mulching with trash reduce shoot borer attack				
	Mechanical control				
	Use of pheromone traps @ 4–5/acre for monitoring; Remove and destroy the dead hearts along with larvae; Installation of light trap with exit option for natural enemies @ 1 per acre				
	Biological control				
	Release 125 gravid females of Sturmiopsis inferens a tachinid parasitoid per acre.; Release Trichogramma chilonis @ 20,000/acre @ 10 days interval at the time of incidence				
	Release 125 gravid females of Sturmiopsis inferens a tachinid parasitoid per acre; Release Trichogramma chilonis @ 20,000/acre @ 10 days interval at the time of incidence.				
	Management of Top borer				
	Mechanical control				
	Collection and destruction of adult moths; Collection and destruction of egg masses; Collection and destruction of dead hearts; Use of pheromone traps @ 4–5/acre for monitoring coinciding with brood emergence; Installation of light trap with exit option for natural enemies @ 1/acre				
	Biological control				
	Release of Trichogramma spp. @ 20,000/acre 2–3 times at 10 days interval				
	Chemical for all borers				
	Chlorantraniliprole 18.5% SC@ 150 ml in 400 L of water/acre				
	Management of Pyrilla				
	Cultural control				
	Avoid late application of nitrogenous fertilizers; Collect and put egg masses in cage to facilitate emergence of parasitoids; Removal and destruction of lower dried leaves.				
	Biological control				
	Release of 3200 to 4000 cocoons or 3.2–4.0 lakh eggs of Epiricania melanoleuca per acre when 3–5 Pyrilla individuals per leaf are seen.; Conserve and augment Epiricanica population from rich to scanty fields				
	Chemical				
	Monocrotophos 36% SL @ 200 ml in 200–400 L of water/acre				
Conventional practice (CP)	Chemical control measures as discussed above				
Ratoon management (for all states)	Recommended management practices for ratoon crop were adopted. Gap filling if gap exceeded 10%; at the time of ratoon initiation, trash mulching, irrigation, nutrients management, biofertilizers application, organic application, subsoiling if required, IPM, earthing-up, cane tying, wrapping, propping etc. (details given in Shukla et al. 2017b)				
Conventional practice (CP)	No gap filing, Normally ratoon initiation after 1 month of harvesting of plant cane and apply chemical fertilizers and irrigation after that. No proper weed management practice adopted				
Drip irrigation (for all states)	Surface drip at recommended row spacing in different states				
Conventional practice (CP)	Flooding/furrow irrigation				

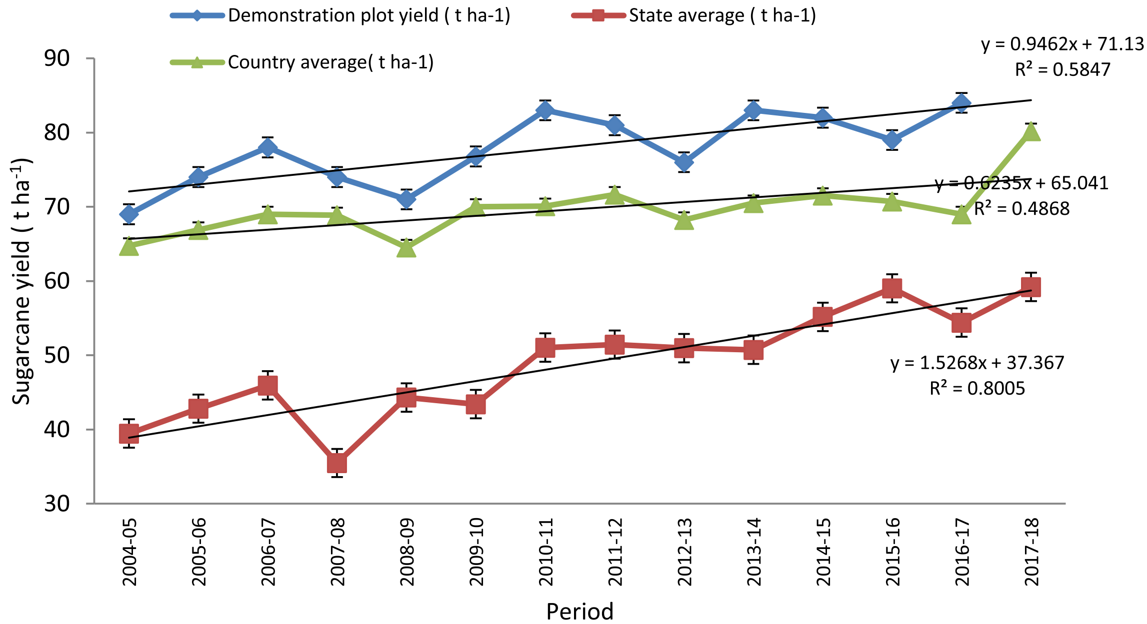

Fig. 6 Relationship between period and sugarcane yields in Bihar

productivity level (> 100 t ha^{-1}) during 2004–2005 to 2011–2012 and during 2014–2015 to 2015–2016, the state witnessed the higher yield decrease (approx. 5 t ha^{-1} in 2012–2013 and 2013–2014 to 20 t ha^{-1} in 2016–2017) which affected the degree of linearity of regression equation ($Y = 0.866x + 107.8$; $R^2 + 0.356/r = 0.596$). During the period, deficit rainfall in state was recorded (Fig. 1) which was main cause of declining sugarcane productivity of state despite availability of technology. In demonstration of technologies also, this pattern could be observed in greater manner ($Y = 0.663x + 108.2$; $R^2 = 0.168/r = 0.41$).

5. *Bihar*

In Bihar, four technologies were demonstrated on farmers' fields. However, the improved variety contributed 40.2% (Table 4) yield increase as compared to state average yield (59.25 t ha^{-1}). The average sugarcane yield of Bihar state was the lowest (59.25 t ha^{-1}) as compared to all other states. Ratoon management (35.14%) and intercropping in sugarcane (31.76%) could also be ranked in the top category in increasing sugarcane yields (Table 4). Integrated weed management could increase the sugarcane yield by 18.24% over the state average yield (59.25 t ha^{-1}). All the technologies could not show any improvement over mean performance of five states. Thus greater scope of improvement in sugarcane yield exists in Bihar, keeping in view the achievable potential and climatic conditions. However, because of low average sugarcane yield of state, the replacement of old varieties could be considered as first most requirement of the state. This could be translated through proper varietal planning, supply of quality seed cane through state sugar mill farms/contact growers and implementing maturitywise harvesting schedule. Intercropping with autumn planted sugarcane provides ample scope of increasing crop yields and farmers profit as well. Details of package of practices adopted in various states have also been provided in Table 5 for understanding the variations in agroecosystems of sugarcane culticvation.

Integrated weed management (IWM) and ratoon management are also required to be considered in holistic manner to improve the sugarcane productivity and profitability at farmers/mill levels. Linear regression equation ($Y = 1.526x + 37.36$; $R^2 = 0.80/r = 0.89$) between crop yields and 13-year period and correlation showed higher degree of positivity in state average cane yield (Fig. 6). However technological demonstrations could increase yield level, and the regression equation ($Y = 0.946x + 71.13$; $R^2 = 0.584/r = 0.76$) showed higher degree of linearity/positivity. During 13-yrs period, Bihar also witnessed few drops in annual rainfall during 2007–2008 and 2009, 2012 and 2015 (Fig. 1) at state level; however, average rainfall was still higher than other states. The adverse effect of low mean annual rainfall on sugarcane yield could also be noticed at the national level during 2008–2009, 2012–2013 and 2016–2017.

Discussion

Sugarcane is a tropical crop and, however, occupies larger acreage in subtropical region of the country (DAC 2018). The application of technologies in both the regions can bring out significant improvements in cane yield. In subtropical region, particularly in Uttar Pradesh and Bihar, low levels of productivity provide better scope of increasing crop yields on farmers' fields due to adoption of advanced technologies. However, in tropical region, the efforts are required to be skewed towards higher achievable potential due to favourable environment (moderate temperature and humidity during elongation phase). The details of adoption of various technologies in different states are being discussed here as under.

Sugarcane yield is influenced by several crop management factors besides genetic makeup (variety) of crop. Availability of irrigation water is second most important component governing crop yield after variety. However, in tropical and subtropical regions of the country > 95% area under sugarcane is irrigated (Sharma et al. 2018). However, being high water requirement crop (1400–2300 mm in subtropical region and 2000–3500 mm in tropical region), the irrigation demand increases under deficit monsoon. The response of various technologies differs in various states. Bihar and Uttar Pradesh are potential states in increasing achievable potential of sugarcane in subtropical region. An evergreen revolution (increase in productivity in perpetuity without associated ecological harm) will come from eastern part of India comprising eastern Uttar Pradesh, Bihar and West Bengal (Swaminathan and Bhavani 2013). Uttar Pradesh falls under subtropical region, and the highest increase (43.85%) was recorded due to pit/trench method of planting. This was followed by adoption of improved variety (27.44%), intercropping with sugarcane (27.44%), drip irrigation (22.40%) and ratoon management (21.14%).

In Uttar Pradesh, greater scope exists in improving sugarcane yield keeping in view the attainable potential of sugarcane. Besides, crop management factor especially pit/trench method of planting showed higher response in increasing sugarcane yield as compared to improved variety and other technologies. This showed that, being vegetative crop, management practices could play higher role as compared to genetic makeup. However, role of improved variety could not be ignored. Pit/trench method of planting pulverized soil up to 45 cm depth and facilitated emergence of mother shoots. This technology discourages emergence of primary and secondary tillers that could become millable cane of shorter length and reduced cane weight. Besides, breaking of hard pan in plough layer due to pit digging/trenching improved root penetration and crop growth and yields. In Uttar Pradesh the effect of method of planting superseded the response of new variety. On farm experiments conducted during 2003 in the field of 96 farmers in 8 districts of Punjab under ring-pit and conventional flat methods of planting indicated 64% higher cane yield in ring-pit method over to the conventional flat method because of the formation of 114% higher millable canes and due to the use of higher amounts of plant nutrients (N and P) in ring-pit method than that in conventional flat method (Yadav and Kumar 2005).

Intercropping in sugarcane increased cane equivalent yields. In Uttar Pradesh, intercropping of mustard, pea, French bean, wheat, potatoes are very common with autumn planted sugarcane. Intercropping of high-value crops such as gladiolus, marigold, vegetables, pulse crops are also being grown (Shukla et al. 2017a). In subtropical India, several short-duration crops have been attempted as intercrops. Maize, especially with autumn planted sugarcane, was evaluated at Banswara, Haryana (Panwar et al. 1990). Wheat has been extensively tested as an intercrop in autumn planted sugarcane and reported to be advantageous compared to sole cropping of cane (Singh and Sharma 1996; Gangwar and Sharma 1997). The short-duration legumes, oilseeds and vegetables were the most suitable intercrops in autumn season planted sugarcane.

Availability of irrigation water has always been critical input for agriculture. Among all the domestic needs of water for farmers, agriculture is the highest consumer of water (Dhawan 2017). Amount and distribution of annual rainfall, crop duration, soil type are factors affecting the irrigation water requirement of crop (Singh et al. 2007). About 40–50% saving could be possible through drip irrigation (Shukla et al. 2017b). Besides, drip irrigation also maintains soil moisture at field capacity, improves nutrient availability and avoids higher temperatures shocks during summer seasons. Thus availability of irrigation water through drip system supports the growth of earlier formed tillers and improves millable canes and cane yield.

Ratoon management also showed great scope in Uttar Pradesh in increasing sugarcane yield. About 21.14% sugarcane yield could be increased over the state average yield through better ratoon management practices. After harvesting of sugarcane crop, normally sugarcane field remains unattended for more than one-month period. Although farmers during that time had focus on supply of cane, sugarcane ratoon gets adversely affected (Shukla et al. 2008, 2013b). This initial negligence causes gaps and decreases the ratoon yields. Sugarcane trash in fields also lies in heaps and mild rains during that period cause growth of *Pythium* fungi (which inhibits sprouting and sometimes causes stubble rotting (Hoy and Schneider 1988)). Thus ratoon management holds great promise in most of the states in sustaining sugarcane and sugar yields. Initial gap filling (if gaps exceeds 10%) through single bud settlings, uprooted stubbles/three bud setts planting, irrigation, stubble shaving, root pruning, trash mulching/interculturing/dismantling of ridges, mild earthing-up, integrated weed management and nutrients management have been key components in managing ratoon cane for sustaining yields. In western Uttar Pradesh, larger area of sugarcane is planted in April–May (summer season) which reduces the period of tillering. In that case, farmers get higher ratoon yields than plant crop/main crop. INM and IWM could increase < 10% yield improvement because most of the farmers already follow practice of manual hoeing and nutrients management; thus, the response of these technologies could not overcome farmers' practice. The most of the researchers recorded sugarcane yields at par with manual hoeing and IWM (Chauhan et al. 1994). However, during scarcity of labourers for interculturing in summer season, IWM proved economic over manual hoeing.

In integrated nutrient management, it could be observed that available nitrogen increased significantly doses of FYM from 12.5 to 25 t ha^{-1} but not to the extent of this. It was also observed that cane yield significantly increased over the farmers practices. The increase in soil nitrogen was due to addition of nitrogen through organic materials and greater multiplication of soil microbes that converted organically bound nitrogen to inorganic form (Bellakki and Badanur 1997; Manjappa 1999). It was observed that application of chemicals and bioagents reduced population of harmful insect-pests and diseases which ultimately improved cane yield. IPM recorded > 10% yield improvements and emphasized its importance. However, there is a need to change the scale of IPM from conventional methods at the field level to a more global approach (Altieri and Nicholls 1999; Webster et al. 2009). Besides farmers apply pesticide after incidence of insect-pest and during the period, initial infection also caused damage and affected crop yields adversely. Thus timely management of insect-pest is essential to save the crop.

In Maharashtra, top three technologies, viz., adoption of improved variety, ratoon management and intercropping in sugarcane, increased sugarcane yield at higher extent. Thicker varieties like Co86032 and CoM0265, Co092005, Co94012 are prevalent varieties having individual cane weight of approx. 2.5–3.0 kg cane weight in Maharashtra (Table 1). Thus variety played significantly higher role over other factors (Abnave Vikas 2019). If we see the achievable potential yield in Maharashtra, it could be recorded as > 300 tonnes ha^{-1} (Gaon Connection 2019). Ratoon management and intercropping could also improve the yields in the range of 26–28% and also considered better options. INM increased sugarcane yields > 20% over the state average sugarcane yield. This emphasized balanced fertilization keeping in view the deteriorating soil organic carbon and emerging micronutrients deficiencies in zinc, iron and boron in Maharashtra (Shukla and Behera 2018). Thus crop residues recycling especially trash management in ratoon/composting of trash and use of organics (press mud cake, FYM, compost, etc.) are important in sustaining soil fertility, making higher water-holding capacity and optimizing rhizospheric environment *vis-a-vis* sustaining sugarcane yields in Maharashtra.

Drip irrigation also recorded better place because of insufficient water availability for irrigation. Water-holding capacity of sugarcane soils in Maharashtra has been poor, and frequent irrigations are required to grow sugarcane crop. In Maharashtra, irrigation water requirement to produce one kg of sugarcane is 292 litres water. Approximate 32 numbers of irrigations are required to complete life cycle of sugarcane crop (Shukla et al. 2017b). However in few areas, *Adsali* crop of 16–18-month duration is also grown which had higher crop productivity also. In Maharashtra, rainfall has always been critical issue for raising sugarcane crop. In this situation drip irrigation has been better option to improve sugarcane yields as well as judicious use of available natural resources.

In Karnataka, the highest contribution in sugarcane yields could be recognized by drip irrigation. It was followed by intercropping, improved variety and ratoon management practices. In Karnataka also, availability of irrigation water had been critical issue in growing sugarcane. Annual rainfall during the years 2007, 2012, 2015–2018 declined at greater rates (Fig. 1), and larger ups and downs increased the importance of drip irrigation due to limited availability of water. Intercropping in sugarcane also had great scope in increasing cane equivalent yields. About 28.79% increase in cane equivalent yields indicated benefits derived through technology because of initial availability of growing space for short-duration component crop in between two rows of sugarcane and minimal adverse effect on growth and yields of sugarcane (main crop). Varietal contribution could be recorded to the tune of 26.32%, and it was found at par with ratoon management. Wide row spacing facilitates the growth of thick varieties and minimizes the seed cane requirement as well besides increasing sugarcane yields by more than 17%. This practice will also facilitate intercropping and drip irrigation in deriving the higher benefits, if implemented together.

Wide row spacing increased cane yield obtained over narrow spacing. Similar results were reported by Malik and Ali (1990) and Yen et al. (2013), where in 1.5-m row spacing, the yield increase of > 12.5 tonnes per ha over 90 cm spacing was recorded. Similarly 150-cm row spacing was successfully attempted in the cane area of M/s Sakthi Sugars Ltd., Erode district, Tamil Nadu, India, which recorded higher yield than 75-cm row spacing. High tillering and low tiller mortality in wide row spacing helped in achieving high yields in spite of the lower seed rate used (Nagendran and Palanisamy 1997). Wide row spacing of 150 cm was preferable for sugarcane-based intercropping systems, and soybean and black gram could be raised as profitable intercrops (Gopalasundaram and Kailasham 2003; Chand et al. 2013).

The highest increase (35.87%) in sugarcane yield in Tamil Nadu state was recorded through pit/trench planting and intercropping. However, improved variety could also increase yield by 33.7% over the state average yield and was found at par with pit/trench planting. Thus stress is also required upon ratoon management, wide row spacing and drip irrigation technologies. These technologies could reflect yield increase to the tune of 20–26% individually as compared to the state average yield. However, if combined together, the larger improvements in yield could be obtained. INM could improve sugarcane yield by 18.48% over the state average yield. Because of higher irrigation water requirement and fluctuations in annual rainfall during 13-year period of study, the state average yield of sugarcane could also be gone down. INM could also find scope of increasing sugarcane yield to the tune of 18.48%, because of emerging multinutrients deficiencies and declining soil organic carbon (Shukla and Behera 2018; Shukla et al. 2018b).

However, keeping in view the potential and past performance of technologies in Tamil Nadu, we could find great scope in increasing sugarcane yield. The constraints faced by farmers could be addressed, and development of varieties for biotic and abiotic stresses is required. So the released varieties could tolerate climatic turbulences effectively and could show their potential.

In Bihar, adoption of improved variety was the highest performing technology in increasing sugarcane yield to the tune of 40.2%. However, ratoon management and intercropping could improve 31–32% sugarcane yields and were required to be intensively focused. Improved weed management could also increase yield > 18% and was found important because of poor management practices adopted and low state average yield (59.2 t ha^{-1}). Thus all the evaluated technologies in Bihar performed well and could improve sugarcane yield in the range of 18–40%. Over all mean of all the technologies in yield improvement was also recorded as 31.32%. It was recorded that about 18.55 t ha^{-1} yield gap in mean cane yield can be narrowed down by adoption of improved technologies in the state.

Summary and Conclusions

Keeping in view the performance of all the demonstrated technologies in five states, viz., Uttar Pradesh, Tamil Nadu, Maharashtra, Karnataka and Bihar, it could be recorded that improved variety played the highest contributing factor in sugarcane yield in Maharashtra and Bihar states. However, in Uttar Pradesh and Tamil Nadu states, pit/trench method of planting superseded the performance of newly evolved varieties. In Karnataka, the sugarcane variety could be placed at third place after drip irrigation and ratoon management. Intercropping with sugarcane also yielded the highest in Tamil Nadu and was found at par with pit/trench planting. Intercropping practice got second status in Karnataka and Uttar Pradesh. In Maharashtra, intercropping with sugarcane could also increase yield significantly and got third rank after variety and ratoon management. The practice of ratoon management received the second rank in Maharashtra and Bihar, third in Karnataka and Tamil Nadu and fourth in Uttar Pradesh. Thus on the basis of rank received in various states, the technologies are required to be prioritized and implemented in effective manner to optimize sugarcane yields.

After finding out yield gaps through 'On farm demonstration plots" and farmers' yield (state average yield), the following conclusions could be drawn.

(1) Mean yield gap through demonstrated technologies in five potential states of the country ranged from 16.88 to 20.90 t $ha^{-1.}$ It reflected that yield improvement in range of 21.30–30.15% could be easily achieved in these states to improve the overall sugarcane productivity.
(2) On the basis of thirteen-year relationship (during 2004–2017) between period and sugarcane yields in different states, it could be concluded that Uttar Pradesh, Maharashtra and Karnataka showed higher degree of closeness between 'yields of demonstration plots' and 'period', whereas Tamil Nadu and Bihar states had higher positive correlation with 'period' and 'state average yield' as compared to 'demonstration plots yields'.
(3) Uttar Pradesh, Maharashtra and Bihar showed higher degree of sustainability in improving sugarcane yields on farmers' fields as well as state level increase.
(4) Improved sugarcane variety, pit/trench method of planting, intercropping with sugarcane, drip irrigation, integrated nutrient management and ratoon management could be focused in potential states of the country to improve the state as well as national average yields of sugarcane.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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