Diversification Options in Sugarcane-Based Cropping Systems for Doubling Farmers’ Income in Subtropical India

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Abstract Crop diversification provides an opportunity for farmers to maximize their profits, fulfilling multiple needs, avoid monsoon threats, and make the crop production system sustainable. Inclusion of various pulse/oilseed/vegetables/cereals/medicinal/aromatic crops with sugarcane brings forth cultivation of these crops in irrigated agro-system and improves the yields of component crops. Besides, the component crops improve soil fertility and create a favorable environment for the further growth of sugarcane crops. Sprouting in winter-initiated sugarcane ratoon could be enhanced by adopting fodder legumes such as Indian clover and Egyptian clover. Intercropping vegetables provides an ample opportunity for mid-season income generation and improves profitability. Besides, high-value medicinal and aromatic crops such as tulsi (holy basil), mentha could also be included in the sugarcane-based system. Crop residue management has been recognized as a critical issue in managing the crops in the various cropping systems. Including multiple bio-agents for fast decomposition of crop residues provides scope for managing soil organic carbon through crop residue recycling in the system. Resource use efficiencies, nutrient use, water use, and weed control could be increased by adopting suitable crops in intercropping systems. An integrated farming system involving crop, livestock, and fisheries options could improve farmers’ profit besides employment generation in rural India. Recyling of bye products and co-products of other enterprises influences the viability and farmer’s profitability of the system. Trash, press mud cake, vinasse, composted bagasse, rhizodeposition of stubble play a significant role in sustaining soil fertility and increasing crop productivity. New emerging crop diversification options, viz., intercropping of rajmash, winter maize, and garlic in autumn cane generate mid-season income and enhance the system’s profitability for small and marginal cane growers. Dual-purpose legumes, viz., cowpea, and green gram as intercrops with spring-planted cane increase the pool of soil microbial biomass nitrogen capitalizing allelopathic effects and sustain soil health. In the present paper, these issues have been discussed. Due to the adoption of location-specific and farmers-centric systems, farmers’ profitability could be increased, providing sustainability to the sugarcane-based systems.

Keywords Autumn planting · Crop diversification · Crop residue management · Farmers’ income · Integrated farming system

Introduction

Sugarcane (Saccharum spp hybrid complex) in India is a commercial crop and occupies second place in agro-based industries after cotton. The area under sugarcane in India revolves around 5.0 million ha at the national level with sugarcane productivity of approximately 78 t/ha during 2020 (Co-operative Sugar 2021) and total sugarcane production 392.80 million tonnes (PIB 2020–21). India produces about 30.56 million tonnes of sugar during 2020–21 and stands second after Brazil in the world (ISMA 2013). During the recent Pandemic of COVID-19 in the country growth of several non-agricultural-based industries was affected adversely. However, the sugar industry could not be affected very much because of several provisions made...
by Govt. for the transport of input and output during lockdown at the country level. Agricultural activities were not disrupted at the more significant level, which could make the livelihood of > 57% of the population in India (Solomon et al. 2020).

The irrigation water requirement of sugarcane in subtropical India is about 1600–2300 mm annually. However, it ranges from 2000 to 3500 mm in the tropical part of the country. The mean annual rainfall of several tropical and subtropical states ranges from 500 to 900 mm (Shukla et al. 2017b). During recent years, aberrant weather situations, viz., floods especially in eastern India and east coast part of the country, drought in the western part of India-Maharashtra, Gujarat, Karnataka, and in the west part of Uttar Pradesh forced farmers to rethink on the sustainability of sugarcane crop in the production system. Besides this, the need for other alternative options to improve water productivity and farmers’ profitability is also available.

Sugarcane requires a higher amount of nitrogen (250–350 kg/ha), phosphorus (60–90 kg/ha), and potassium (60–120 kg/ha) besides other secondary (sulfur) and micronutrients (Zn and Fe) depending on nutrient deficiencies in the soil (Mishra et al. 2014). Sugarcane crop generates about 10–12 t/ha trash (dry crop residues) annually. Trash mulching in subsequent ratoon crops conserves soil moisture, controls weed growth, and enhances soil organic carbon after decomposition. Thus integrated nutrient management involving organic, inorganic sources, biofertilizers, green manuring, etc., holds great promise in sustaining soil fertility and crop productivity in sugarcane-based systems (Shukla et al. 2007; Yadav et al. 2009a; Yadav and Shukla 2016).

Most of the pulse and oilseeds crops are grown on marginal lands in India. Farmers are also not following recommended package of practices for these crops because of unawareness and financial crunch. Sometimes unavailability of quality inputs in the nearby market also poses problems before growers. Intercropping of pulses and oilseeds with sugarcane could provide new avenues for the growth of these crops in the irrigated agroecosystem. Thus, the productivity of these component crops could also be improved at a greater level. In this series, intercropping of mustard with autumn sugarcane has also been found an economically viable option (Shukla and Pandey 1999) compared to the mustard-sugarcane sequential system.

At the ICAR-Indian Institute of Sugarcane Research, Lucknow, intercropping of French bean has been found remunerative compared to other crops in autumn sugarcane. Intercropping two rows of potato with October planted sugarcane produced a similar yield of both the crops as planted sole. However, residual fertility level after harvesting of potato maintained the higher yield of sugarcane as well (Singh et al. 2020; Shukla et al. 2021). Thus land-use efficiency could be increased through intercropping in sugarcane. Weed management in sugarcane has also been found to be a critical issue during 90–120 days after planting. Intercropping also controls weed growth and can minimize chemicals besides economizing other inputs.

About 89% of holdings belong to marginal and small farmers in India. The landholding size decreased over the period and came down to 1.12 ha (All India Report on Agriculture Census 2015–16). Farm mechanization has been mainly concentrated on the tractorisation of agriculture. However, Combine Harvester is practiced in food grain crops, viz., rice, and wheat. Farmers also procure these machines on a custom and hire basis. In sugarcane, most operations require a separate device like Furrow Opener cum Planter, FIRB Planter, Inter-culturing equipment’s, Ridge Maker, Harvester, etc. Thus small equipment performing quality operations can sustain marginal and small growers. An integrated farming system approach involving crop, livestock, and fisheries options could improve farmers’ profit besides the employment generation of rural people. Recycling of bye products and co-products of other enterprises influences the viability and farmers’ profitability of the system. At IISR Lucknow, sugarcane-based IFS models for marginal and small farmers had been developed for improving yield and income (Dwivedi et al. 2020).

In the subtropical part of India, especially the western part of Uttar Pradesh, a larger sugarcane area (> 1 million ha) is planted in April–May after harvesting the wheat. In the wheat–sequential sugarcane system, planting of sugarcane is delayed due to harvesting of wheat in April. Thus tillering period in sugarcane is reduced, which adversely affects the population of millable canes. Besides the shortened growth period, individual cane weight and cane thickness are also reduced, which results in poor sugarcane yield in plant (main) crops. However, farmers focus on ratoon and compensate for their cane yield. Simultaneous planting of sugarcane and wheat in November–December opened new avenues to increase sugarcane productivity without affecting the yield of the wheat crop. A new system of FIRBS (Furrow Irrigated Raised Bed System) has also been introduced to improve sugarcane and wheat yields. Planting of sugarcane setts in standing wheat crop in the last week of February to the first week of March has been found an economically viable option (Singh et al. 2012; Shukla et al. 2017b). In this system, the furrow of sugarcane is left vacant at the time of planting after 2/3 rows of wheat sown on raised beds through Raised Bed Planter. Planting of 2/3 bud setts is done during the last week of February/first week of March in a standing wheat crop after irrigation. Sets are pressed manually, and a good plant stand is observed while harvesting wheat in April. Harvesting of wheat can be done manually or
through Combine Machine without any adverse effect on standing sugarcane crop grown in the system. Thus, decline in the yield of sugarcane plant crops could be arrested because of spring planting (Feb–March) in the same system.

Keeping the above points in view, the diversification options with sugarcane planted in different seasons holds excellent promise for sustainability and farmers’ profitability. Site-specific problems could be addressed besides fulfilling the multiple needs of farmers by integrating various commodities. Recycling of bye-products/ co-products also provides viability to another enterprise, which could reduce the cost of the production system. The present paper discussed various diversification options for improving farmers’ profitability and sustainability. Major issues and different profitable cropping/farming systems are being discussed below.

**Intercropping with Autumn Sugarcane**

About 15% of sugarcane area comes under autumn (October) planting in subtropical India. Here, after germination, the minimum temperature (< 8–10 °C) prevails in December and January due to the winter season. Crop growth triggers after improving the minimum temperature in the spring season (After February). In autumn, sugarcane, in subtropical India, tillering is almost ceased during the winter season (November–January), and it favors the growth of any other component crop/ intercrop. Although through several experiments, it has been proved that autumn crop could increase sugarcane yield by 20–25% over spring planting besides increasing sugar recovery by 0.5–1.0 units (Shukla et al. 2017a). However, autumn planting could not be adopted to a more significant extent because of losing one winter (rabi) season crop. In subtropical India, the duration of the autumn crop (15–16 month) vis-à-vis the spring crop (12 month) focused much attention on farmers (Shukla et al. 2019; Singh et al. 2021; Lal and Singh 2004). Adopting early maturing sugarcane varieties also plays a significant role in improving sugar recovery. If planted in spring, early maturing varieties may be harvested in the coming December. However, if these varieties are grown under autumn cultivated conditions, it may improve sugar recovery with tonnage if harvested in Nov–Dec.

**Sugarcane + Legume (Pulse) Based System**

Pulses are a rich source of protein and are known for quality food grains among the vegetarian community of the country. Protein malnutrition in developing countries is a significant concern and through the consumption of pulses, the deficiency could be addressed. By 2020, the production of pulses in India reached 24.42 million tonnes (PIB 2020–21). Development of improved varieties of various pulse crops, and their adoption in irrigated agroecosystem brought forth the productivity of pulse crops in India (Shukla et al. 2017a; Geetha et al. 2019). Due to stagnant production and an increase in population, the per capita availability of pulses declined in the range of 35.4–47.2 g/capita/day during 2009–2014 (Dhaker et al. 2021). A significant increment in area and productivity of pulse crops could also be possible by intercropping these crops with autumn sugarcane. Thus, in irrigated agroecosystem, there is an excellent scope of the increasing area under pulse crops through crop diversification/intensification besides improving their productivity.

Legume intercrops in cropping systems enhance soil fertility through the excretion of amino acids into the rhizosphere. The nitrogen fixed by the legume intercrop may be made available to the associated sugarcane in the current season itself, as sugarcane remains in the field for over nine month after the harvest of the legumes. A further possibility of soil fertility improvement is through the addition of crop residues, which on decomposition adds to the fertility of the soil. Since considerable addition of nutrients occurs through intercrop, there is a possibility of reducing N application through fertilizer. With the introduction of machinery in sugarcane cultivation to address the scarcity of workforce besides cost reduction and the adoption of high tillering and high yielding varieties of sugarcane, there is a possibility to adopt wider row spacing and still sustain cane productivity. Such wide row spacing permits intercropping without adversely affecting the cane yield and thus increases the overall productivity and profitability of the system. The present problem of labor shortage may worsen in the future, affecting the survival of the sugar industry and cane growers. Wide row spacing becomes an important agronomic consideration in the future in developing country like India.

Intercropping of pulses, viz., *rajmash*, chickpea, lentil with autumn (October)-planted cane in the furrow-irrigated raised-bed system (FIRBS) fits well to improve the crop yields. Here, sugarcane is grown in furrows, and intercrops are planted on raised beds. The system provides excellent scope for increasing crop productivity and optimizing input use efficiencies. Intercropping French beans with autumn sugarcane has been found profitable at IISR Lucknow (Singh et al. 2020). Intercropping two rows of French bean (PDR-14) showed a distinctly positive effect on sugarcane growth similar to potato in terms of shoot count at the grand growth stage. The system appeared to be quite profitable as it yielded a 1664 kg/ha yield of French bean. Chickpea can be managed efficiently with autumn (October) planted sugarcane and resulted in 25% N economy (Lal and Singh 2004).
Resource use efficiencies (nitrogen use efficiency, weed control efficiency, water use efficiency, etc.) and land equivalent ratio could be improved through intercropping pulse crops with sugarcane. Autumn sugarcane intercropped with two rows of lentils (DPL 15) receiving 150 kg N/ha in combination with Azospirillum produced the highest sugarcane equivalent yield, which was, however, comparable to the suboptimal dose of 112.5 kg N/ha (Lal and Singh 2004).

These observations indicate that intercropping sugarcane with two rows of lentils could affect savings of 37.5 kg N/ha (Shukla et al. 2017a). The compatibility of pulses as intercrop in sugarcane for enhancing system productivity has also been documented (Tables 1 and 2). Intercropping of high-density early-bulking forage crops (Egyptian clover/Indian clover) enhances bud sprouting in winter initiated ratoon by regulating rhizospheric thermal regime and serving as live mulch to protect sprouts from frost/cold damage during severe winter (Shukla et al. 2007). Egyptian clover-berseem after cuttings left the highest amount of available N in the soil (243.5 kg/ha in 0–15 cm and 233.6 kg/ha in 15–30 cm soil layer) besides improving the physical conditions of the soil (Shukla et al. 2017a). An economic evaluation of various intercropping systems with autumn sugarcane indicated the highest B/C ratio (2.16) with the sugarcane + rajmash system. At IISR, Lucknow, under the National Agricultural Technology Project on ‘Intercropping of different crops with sugarcane,’ the highest cane equivalent yield (112.85 t/ha) was obtained in sugarcane + rajmash system and the lowest cane equivalent yield (76.33 t/ha) and B/C ratio (1.02-IISR 2007-08-Table 3).

Geetha et al. (2019) at Coimbatore recorded the profitability of the sugarcane + soybean intercropping system among the five legume intercrops in sugarcane. Sugarcane + soybean recorded a higher cane equivalent yield (CEY) of 132.0 t/ha, followed by sugarcane + green gram (119.4 t/ha). Sugarcane + sun hemp has recorded a higher land equivalent ratio (LER) of 1.39, followed by green gram (1.37) and soybean (1.21) when compared to the sole crop of sugarcane. Weed smothering efficiency (WSE) was significantly higher in the sugarcane + cowpea (36.3%) intercropping system followed by sun hemp (32.3%) and soybean (32.0%) over the sole sugarcane (control). The highest gross return (Rs. 376,243/ha) was obtained from sugarcane + soybean followed by sugarcane + green gram (Rs. 340,242/ha), and it was lowest in sole sugarcane (Rs. 211,771/ha). Similarly, the highest benefit-cost ratio (1.83) was observed in sugarcane + soybean, while lowest in sole sugarcane (1.06). Based on cane yield, cane equivalent yield, and returns per rupee of investment, it was inferred that, among all the cropping systems, sugarcane + soybean was found to be most profitable under a wide row of planting than the cultivation of sole sugarcane in the tropical region of India.

Crop residues recycling of pulses addresses the vital issue of decreasing soil organic carbon created due to indiscriminate/imbalanced use of fertilizers and lower use/unavailability of organic manures (Shukla et al. 2007). Mechanization of diversified cropping systems is required to boost the adoption of recommended technologies by the farmers. Various tractor-drawn implements for planting sugarcane and component pulse crops have been developed. A combine machine for harvesting pulse crops has already been designed and is being used by the farmers. Thus, the cost of production could be reduced, and higher profitability could be ensured with the introduction of these crops in an irrigated agroecosystem. Besides the decline in soil organic carbon could also be arrested, which provides sustainability (Yadav et al. 2009a; b).

### Sugarcane + Vegetables Based Cropping System

The area under an intercropping system in sugarcane in Uttar Pradesh has increased significantly in the recent past due to higher net returns as compared to other field crops.

| Sugarcane Production | Suitable Crops |
|----------------------|----------------|
| Tropical Belt        | Green gram (*Vigna radiata*); Black gram (*Vigna mungo*); Cow pea (*Vigna unguiculata*); Soybean (*Glycine max*); Ground nut (*Arachis hypogea*) |
| Subtropics (Autumn planting) | Lentil (*Lens culinaris*); French bean (*Phaseolus vulgaris*); Peas (*Pisum sativum*) |
| Subtropics (Spring planting) | Green gram (*Vigna radiata*); Cow pea (*Vigna unguiculata*); Dhaincha (*Sesbania sesban*) and Black gram (*Vigna mungo*) etc. |
| Subtropics (ratoon crop) | Berseem-Egyptian clover (*Trifolium alexndrium*); Shaftal Persian clover (*Trifolium resupinatum*); Alfalfa (*Medicago sativa*) and Menthi-Fenugreek (*Trigonella fonum-graceum*) |
Out of the total area under sugarcane cultivation (27.40 lakh ha) in Uttar Pradesh during 2020–21, the acreage under intercropping in sugarcane (autumn and spring seasons) was 4.24 lakh ha in different districts across the state, as per information obtained from the office of the Cane Commissioner, Govt. of Uttar Pradesh. Thus, the share of higher acreage under intercropping in sugarcane in Uttar Pradesh speaks of the significant impact of technology on intercropping in sugarcane for higher yield and profit (Cane Commissioner Report 2020).

In the case of sugarcane, much of the space between two rows of sugarcane remains unutilized for an initial period of 90–120 days due to slow crop growth. Intercropping offers an opportunity for the profitable utilization of available space. Sugarcane growers can take advantage of this and grow various short-duration crops like cereals, pulses, vegetables, and spices as intercrops to obtain an interim return. Small sugarcane growers need not wait until the harvest of the sole crop to bring financial returns. Intercropping of economically important short duration crops with sugarcane through the utilization of the present limited land resources would help to sustain sugarcane cultivation and provide an interim return to marginal and small farmers, besides meeting the ever-increasing demand for vegetable sand pulses. Several studies demonstrated that the total productivity of crops in the sugarcane + vegetables intercropping system is substantially higher than the total productivity of the sole rabi crop in winter, followed by sole sugarcane planted in the spring season. In Table 4, various sugarcane + vegetable systems conducted on farmers’ fields are being discussed (Singh et al. 2018).

**Sugarcane + Oilseed Crop-Based System**

Growing oilseed crops such as mustard and rapeseed (to-ría) with autumn planted sugarcane in subtropical India is very common to improve the land-use efficiency and crop equivalent yields (Shukla and Pandey 1999). Govt. of India has focused upon improving oilseed productivity and area to make self-sufficiency in edible oils. However, despite all efforts, huge money (> Rs. 80,000 crore) is spent on the import of oil in the country (PIB 2020–21). National Technology Mission to improve the productivity of oilseed crops was also launched in the 1986. However, we could reach the level of 36.10 million tonnes annual production of oilseed crops (PIB 2020–21). Intercropping of oilseed crops with autumn sugarcane is feasible and can change the domain of oilseed crops from marginal rain-fed conditions to irrigated agroecosystems. This may result in an expansion of area and productivity because of better management practices. Short duration, erect growing, dwarf varieties of

| Cropping System                        | Yield (t/ha) | Sugarcane Equivalent Yield (t/ha) |
|----------------------------------------|-------------|-----------------------------------|
|                                       | Sugarcane   | Intercrop                          |
| Sugarcane sole (Co 6304)               | 81.00       | –                                  | 81.00 |
| Sugarcane + Fieldpea (Rachna)          | 80.34       | 0.62                               | 92.09 |
| Sugarcane + Fieldpea (Pusa 10)         | 81.16       | 0.44                               | 88.78 |
| Sugarcane + Fieldpea (HFP 4)           | 76.38       | 0.54                               | 85.45 |
| Sugarcane + Rajmash (PDR 14)           | 78.14       | 0.72                               | 99.85 |
| Sugarcane + Rajmash (VL 63)            | 88.12       | 1.00                               | 111.13|
| Sugarcane + Chickpea (JG 74)           | 77.58       | 1.14                               | 96.11 |
| Sugarcane + Chickpea (JG 315)          | 76.58       | 1.19                               | 94.28 |

Table 2: Effect of various pulses with autumn sugarcane. Source: Shukla et al. (2017a)

| S. No | Cropping systems       | Cane Yield (t/ha) | Cane Equivalent Yield (t/ha) | B:C ratio |
|-------|------------------------|-------------------|-------------------------------|-----------|
| 1     | Sugarcane (sole)       | 76.33             | 76.33                         | 1.02      |
| 2     | Sugarcane + lentil     | 65.00             | 83.53                         | 1.10      |
| 3     | Sugarcane + rajmash    | 83.00             | 112.85                        | 1.53      |
| 4     | Sugarcane + mustard    | 72.66             | 96.53                         | 1.33      |
| 5     | Sugarcane + toria      | 70.67             | 88.64                         | 1.17      |

Table 3: Economics of various cropping systems. Source: IISR (2007–08)
crops are more suitable for intercropping with sugarcane than tall, spreading, and longer duration varieties. Few short-duration genotypes/varieties of Indian mustard (*Brassica juncea*) having erect nature have been developed through biotechnological tools. Bio 417 has been found fit for intercropping with autumn sugarcane (Shukla and Pandey 1999).

At the IISR, Lucknow, sole sugarcane (autumn) showed the lowest mean cane equivalent yield (82 t/ha). The intercropping and sequential cropping treatments increased the cane equivalent yield by 14 and 13.5%, respectively. The highest cane equivalent yield (99.75 t/ha) was obtained by intercropping Bio 417 mustard with autumn sugarcane. It was followed by Bio 417-spring cane (Shukla and Pandey 1999).

In subtropical India, the intercropping of mustard or potato in sugarcane on microbial diversity, soil quality, and crop productivity was assessed (Singh et al. 2021). The systems consisted of sugarcane + mustard–ratoon–cowpea, sugarcane + potato–ratoon–wheat and standard sugarcane–ratoon–wheat rotation. The sugarcane-potato-ratoon-wheat system recorded a significantly higher cane equivalent yield (120.4 t/ha) than sugarcane + mustard-ratoon-cowpea (109.4 t/ha) and sugarcane-ratoon-wheat (92.6 t/ha), which produced cane equivalent yield higher in the tune of 10.1 and 30.0%, respectively. However, the most increased microbial activities (microbial counts, Table 4 Details of varieties, row arrangement, date of sowing/harvesting, seed rate, and fertilizer application for different intercrops in a vegetable-based system. *Source*: Singh et al. (2018)

| Intercropped Vegetables | Variety | No. of Intercrop Rows in Between Two Cane Rows | Date of Sowing | Plant to Plant Distance (cm) | Seed Rate (kg/ha) |
|-------------------------|---------|-----------------------------------------------|---------------|-----------------------------|------------------|
| Cauliflower (*Brassica oleracea var. botrytis* L.) | PSB-16 | Two | First Fortnight of November | 45 | 0.350 (for nursery) |
| Cabbage (*Brassica oleracea var. Capitata F. alba*) | Pride of India | Two | First Fortnight of November | 45 | 0.400 (for nursery) |
| Knol-khol (*Brassica oleracea var. Caulorapa O.C. Linn.*) | King of North | Three | First Fortnight of November | 20 | 0.450 (for nursery) |
| Turnip (*Brassica rapa* L.) | PTWG | Three | First Fortnight of November | 20 | 0.800 |
| Carrot (*Daucus Carota* L.) | PusaKeshar | Three | First Fortnight of November | 10 | 3.50 |
| Radish (*Raphanussativus* L.) | Jaunpuri | Three | First Fortnight of November | 10 | 7.00 |
| Potato (*Solanum tuberosum* L.) | C-3797 | Two | First Fortnight of November | 20 | 2200 |

Table 5 Sugarcane and mustard intercropping system influencing cane equivalent yield. *Source*: Shukla and Pandey (1999)

| Treatment | Sugarcane Yield (t/ha) | Mustard Yield (t/ha) | Cane Equivalent Yield (t/ha) |
|-----------|------------------------|----------------------|-----------------------------|
| Mustard (Pusa Jai Kisan)-Spring cane | 67.4 | 1.76 | 95.94 |
| Mustard (Bio 417)-Spring cane | 66.0 | 1.96 | 97.98 |
| Mustard (Bio165-92)-Spring cane | 64.3 | 0.95 | 79.80 |
| Mustard (Bio 613-92)-Spring cane | 69.3 | 1.52 | 94.35 |
| Mustard (Varuna)-Spring cane | 67.3 | 1.87 | 97.62 |
| Sole sugarcane (Autumn planting) | 82.0 | – | 82.00 |
| Mustard (Pusa Jai Kisan) + Autumn cane | 69.6 | 1.39 | 92.14 |
| Mustard (Bio 417)-Autumn cane | 74.3 | 1.57 | 99.75 |
| Mustard (165-92)-Autumn cane | 76.7 | 0.76 | 89.09 |
| Mustard (Bio 613-92)-Autumn cane | 75.9 | 1.10 | 93.74 |
| Mustard (Varuna)-Autumn cane | 70.1 | 1.52 | 94.75 |
| CD (P = 0.05) | 8.70 | 0.20 | 6.90 |
microbial biomass carbon and nitrogen and basal soil respiration), soil enzymes, total carbon (T.C.) and nitrogen (T.N.), available N, Zn, Cu, Fe, and cation exchange capacity (CEC) were recorded for sugarcane + mustard-ratoon-cowpea system. Thus intercropping of mustard or potato in sugarcane could be the way to increase crop productivity in limited land resources in the subtropical part of India (Singh et al. 2021). Intercropping of potato with autumn sugarcane improved cane yield and N use efficiency also as compared to the potato-sugarcane sequential system (Shukla et al. 2020c). Application of S and Zn fertilizer and recommended NPK improved tuber weight besides increasing sugarcane yield in the intercropping system (Tables 6 and 7).

Intercropping with Spring-Planted Sugarcane

About one million hectares additional area can be brought under pulses by intercropping short duration pulse crops, viz., green gram and black gram in spring-planted sugarcane, especially in Uttar Pradesh, north Bihar, Punjab, and Haryana. Experiments conducted at IISR Lucknow proved that out of five varieties of green gram, minimum reduction (4–5%) in sugarcane yield occurred with PDM-11 and PDM-84-139. Among dual-purpose legumes, the highest net monetary return was worked out for the sugarcane + green gram (K-851 for grains) system followed by sugarcane + cowpea (Pusa Komal for green pods) (Singh et al. 2020). After picking green pods for vegetables and/or mature pods for grains, the legume plants with longer leaf area duration were incorporated in the soil between the inter-row spaces of sugarcane as green manure.

These systems affect nitrogen economy in sugarcane to the extent of 35–40 kg/ha besides producing a bonus yield of pulses. The compatibility of intercrops varies with the row arrangements (Yadav et al. 1987) and genotypes selected as intercrops in the system (Lal et al. 2000). In a field study conducted at the IISR Lucknow, green gram as an intercrop of spring-planted sugarcane yielded 2.6 quintals grain/ha, almost equivalent to 4.18 tonnes of cane/ha. Sugarcane growth and yield were also not affected adversely. Subsequent ratoon raised from mung bean (green gram) intercropped plant crop yielded higher than that raised from sole sugarcane. The benefits were to the tune of 18–20 t/ha of sugarcane. At Padegaon, intercropping of lucerne and berseem (leguminous fodder crops) with sugarcane did not raise the fiber content of cane rather decreased it marginally. Reduction in cane yield to the extent of 15.2 and 14.6%, respectively, was observed due to intercropping of Lucerne and berseem at Dapoli. However, the juice quality remains unaffected (Ghosh et al. 1990). The economic evaluation of different crop sequences revealed that cowpea-potato-mustard-mung bean rice-cane + potato sequence gave the highest profit at IISR farm and on farmers’ fields. Therefore, paddy-sugarcane + potato/mustard-ratoon-wheat/mung bean/red bean/cowpea; Kharij legumes-autumn cane + mustard-ratoon-wheat/grain legumes; maize-potato/mustard-spring cane + urd bean/cowpea/mung bean-ratoon-wheat; paddy-wheat-sugarcane-ratoon-grain legumes and paddy-wheat-sugarcane-ratoon + berseem/mung bean/wheat cropping systems meet the multiple needs of the farmers under subtropical condition and were found suitable (Shukla et al. 2017b).

Sugarcane Ratoon in Various Cropping Systems

Sprouting of winter initiated ratoon is the major constraint in ratooning under subtropical conditions. Sugarcane varieties under the All India Coordinated Research Project

| Cropping System | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ | $T_9$ | CS (Mean) |
|-----------------|------|------|------|------|------|------|------|------|------|-----------|
| $Potato\ Yield\ (t/ha)$ |      |      |      |      |      |      |      |      |      |           |
| C$_1$-(P-S)     | 22.50 | 31.33 | 32.83 | 34.83 | 33.83 | 33.67 | 34.17 | 35.83 | 37.83 | 32.98     |
| C$_2$-(P+S)     | 21.00 | 30.00 | 29.83 | 33.93 | 35.50 | 32.23 | 33.03 | 33.17 | 34.60 | 31.48     |
| Sub-Plot Mean   | 21.75 | 30.67 | 31.33 | 34.38 | 34.67 | 32.95 | 33.60 | 34.50 | 36.22 | GM = 32.23 |
| SE (CS): 6.63 CD(CS): NS; SE (NM): 10.10 CD(NM): 33.56; SE (CS×NM): 15.01 CD: (CS×M): NS |
| $Average\ Tuber\ Weight\ (g)$ |      |      |      |      |      |      |      |      |      |           |
| C$_1$-(P-S)     | 42.87 | 53.87 | 56.00 | 56.17 | 58.00 | 54.83 | 54.33 | 55.00 | 56.33 | 54.16     |
| C$_2$-(P+S)     | 37.05 | 52.00 | 53.67 | 53.00 | 54.83 | 54.00 | 54.67 | 55.33 | 56.73 | 52.37     |
| Sub-Plot Mean   | 39.96 | 52.93 | 53.83 | 54.58 | 56.42 | 54.42 | 54.50 | 55.17 | 56.53 | GM: 53.26  |
| SE (CS): 0.81 CD(CS): NS; SE (NM): 0.74 CD( NM): 2.45; SE (CS×NM): 1.28 CD: ( CS×M): 4.75 |
on Sugarcane (AICRP-S) are developed based on the mean performance of two plant crops and one ratoon in advanced varietal trials. Thus weightage on ratoon is lower in working out a mean yield of sugarcane variety recommended for a particular zone. Earlier in subtropical India, early maturing high sugar varieties were considered poor ratooner. However, after the development of early maturing varieties, viz., Co0238, CoLk 94184, and CoPk05191, the situation improved and these varieties showed their higher yield potential, rationality besides having improved sugar content during the early period of crushing. Introducing early-bulking high-density intercrops (Egyptian clover, Persian clover, and Indian clover) can mitigate the problems associated with winter-initiated ratoon. Moreover, intercropped forage legumes serve as live much, regulate the rhizospheric thermal regime through root respiration, protect stubble buds from frost damage and encourage the sprouting of subterranean buds during the winter season.

Rice–wheat rotation is predominant in the north-central and north eastern plain zone of the country (Chauhan et al. 2012). However, the sugarcane-ratoon-wheat system is primarily adopted in North West plain zone of the country. Productivity and profitability of rice–wheat cropping systems are comparatively lower than sugarcane-ratoon-wheat systems. Annual rainfall is higher in rice-growing areas (eastern Uttar Pradesh, Bihar, West Bengal, and part of Assam) than the dominant sugarcane belt (western part of Uttar Pradesh). The irrigation water crisis is faced in several blocks of the Muzaffarnagar district in Uttar Pradesh (Umar 2020). Despite this, the highest mean cane yield (> 80 t/ha) of the Muzaffarnagar District was also recorded (Rahman and Bee 2019) during 2019–20. Thus alternative options are needed to make the cropping system more profitable and viable.

Furrow Irrigated Raised Bed (FIRB) system of wheat sowing saves 25–30% water and facilitate mechanical weeding (Bhullar et al. 2006). The system reduces cane lodging and seed requirements of the component crop. In the FIRB system of wheat, furrows are available for planting sugarcane in standing wheat from October to March. Sugarcane grown in furrows provides a better option for realizing higher productivity and net returns. In this system, wheat sown on raised beds may negate the overcrowding effects on sugarcane due to spatial variation (Dhillon 2002a, b).

| Cropping System | Sugarcane Yield (t/ha) | Sucrose (%) juice | CCS (t/ha) | N use Efficiency (%) |
|-----------------|------------------------|-------------------|-----------|---------------------|
| C1-Potato-Sugarcane | 87.3                   | 15.98             | 9.48      | 38.4                |
| C2-Potato+Sugarcane | 103.5                  | 17.05             | 11.86     | 45.1                |
| SE m ±          | 1.40                   | 0.032             | 0.11      | 0.62                |
| CD (P = 0.05)   | 4.10                   | 0.10              | 0.32      | 1.84                |

| Nutrient Management | Sugarcane Yield (t/ha) | Sucrose (%) juice | CCS (t/ha) | N use Efficiency (%) |
|----------------------|------------------------|-------------------|-----------|---------------------|
| T1-Absolute control (No N, P, K) | 61.6                   | 16.39             | 6.76      | 0                   |
| T2-Recommended dose of N, P, K | 93.8                   | 16.47             | 10.45     | 35.0                |
| T3-Recommended dose of N, P, K, S | 97.7                   | 16.9              | 11.18     | 42.5                |
| T4-Recommended dose of N, P, K, S, Zn | 101.6                 | 16.29             | 11.22     | 44.0                |
| T5-Recommended dose of P through NPS 1# | 95.9                   | 16.72             | 10.83     | 39.0                |
| T6-Recommended dose of P through NPS 2# | 98.9                   | 16.19             | 10.81     | 35.0                |
| T7-Recommended dose of P through NPSZn # | 102.6                 | 16.65             | 11.60     | 44.0                |
| T8-Recommended dose of NPK+Sulphur and Zn equivalent to NPSZn supplied in T3 | 105.6                 | 16.66             | 11.88     | 45.0                |
| SE m ±          | 2.30                   | 0.05              | 0.15      | 0.78                |
| CD (P = 0.05)   | 6.7                    | 0.15              | 0.42      | 2.25                |

Source: Shukla et al. (2020c)

Table 7 Effect of potato and sugarcane-based cropping system and nutrient management schedule on sugarcane yield and quality parameters.
**Sugarcane + High Value Medicinal/Spices/Aromatic Crops-Based System**

Intercropping high-value crops such as gladiolus, marigold, vegetables, and pulse crops are also being adopted in various sugarcane growing regions (Shukla et al. 2017b). 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). Including high-value medicinal and aromatic crops is also a viable option in an intercropping system with sugarcane. At the IISR, Lucknow, sequential cropping with wild marigold recorded the highest wheat equivalent yield (95.5 t/ha) under *Tulsi*-Wild Marigold (Two cuts)-Sugarcane (spring)-Sugarcane ratoon-Mint cropping sequence. All the cropping sequences of medicinal and aromatic plants (except two cutting of Wild Marigold and Stevia) recorded significantly higher cane yield than Rice–Wheat–Sugarcane (Spring)-Sugarcane Ratoon-Wheat cropping sequence (IISR 2020). Profitability of various cropping systems with sugarcane has been given in Table 8. Among all the cropping systems, sugarcane + garlic/ fenugreek produced higher equivalent yield advantage and also showed the highest B:C ratio (Table 8).

**Intercropping and Juice Quality**

As regards sucrose content in cane juice, the different intercrops had no significant effect on juice quality parameters, especially sucrose content in cane juice which varied from 15.93 to 19.0% in other systems. These results align with those reported by Shukla and Pandey (1999) and Li et al. (2011). Srivastava et al. (2015) analyzed the positive effect on sucrose percent juice (by 0.5 units) due to the adoption of intercropping system with an autumn cane as compared to a spring cane. However, intercropping of winter pulses with autumn sugarcane optimizes higher net return with improved resource use efficiency. No adverse effect of sugarcane main crop/ratoon crop on the quality of intercrop (component crop) has been reported.

### Table 8 Profitability of various sugarcane based cropping systems in India

| Cropping system               | Equivalent yield advantage over sole crop (t/ha) | Benefit: cost ratio | References                  |
|-------------------------------|-----------------------------------------------|---------------------|-----------------------------|
| Sugarcane + Legume (pulse)    |                                               |                     |                             |
| Sugarcane + Lentil             | 18.53                                         | 1.10                | IISR (2007–08)              |
| Sugarcane + Rajmash            | 29.85                                         | 1.53                | IISR (2007–08)              |
| Sugarcane + Green gram         | 45.09                                         | 1.66                | Geetha et al. (2019)        |
| Sugarcane + Vegetables         |                                               |                     |                             |
| Sugarcane + cauliflower        | 42.6                                          | 1.58                | Singh et al. (2018)         |
| Sugarcane + Cabbage            | 46.65                                         | 1.65                | Singh et al. (2018)         |
| Sugarcane + Knoll khol         | 45.04                                         | 1.62                | Singh et al. (2018)         |
| Sugarcane + Turnip             | 35.28                                         | 1.41                | Singh et al. (2018)         |
| Sugarcane + Carrot             | 29.31                                         | 1.30                | Singh et al. (2018)         |
| Sugarcane + Radish             | 18.56                                         | 1.12                | Singh et al. (2018)         |
| Sugarcane + Potato             | 84.94                                         | 1.97                | Singh et al. (2018)         |
| Sugarcane + Oilseeds           |                                               |                     |                             |
| Sugarcane + Mustard            | 13.87                                         | 1.33                | IISR (2007–08)              |
| Sugarcane + T                  | 17.99                                         | 1.17                | IISR (2007–08)              |
| Sugarcane + Garlic             | 150.75                                        | 4.10                | Singh et al. (2020)         |
| Sugarcane + Ridge gourd        | 44.8                                          | 2.40                | Gouri et al. (2015)         |
| Sugarcane + Other high value crops |                                         |                     |                             |
| Sugarcane + Coriander          | 16.4                                          | 1.87                | Gouri et al. (2015)         |
| Sugarcane + Fenugreek          | 139.25                                        | 4.77                | Singh et al. (2020)         |
| Sugarcane + Gobhi sarson       | 15.86                                         | 1.32                | Kumar et al. (2015)         |
| Sugarcane + Celery             | 15.40                                         | 1.29                | Kumar et al. (2015)         |
**Crop Residue Management in the Cropping System**

In various cropping systems, field operations (plowing intercultural, harvesting, etc.) at proper timing are the most critical issue which can be taken up through mechanization. Adopting early maturing varieties and incorporating short-duration crops as intercrop are other management strategies to improve the profitability of the cropping system. Residue recycling provides ample scope to sustain soil fertility and enhance crop productivity in an irrigated agroecosystem. Simple incorporation of rice residue may cause nutrient immobilization and yield reduction in subsequent wheat. Thus residue stubble decomposition can be enhanced by inoculation of cellulytic fungi such as *Trichoderma* (Yadav et al. 2009b). *Trichoderma* has shown to have significant decomposing activity of combined harvested paddy straw when incorporated with silica-solubilizing bacteria and *Pleurotus* and showed higher yield in succeeding rice crop (Meena et al. 2014).

Soil microorganisms regulate nutrient transformation processes and are essential for agricultural systems’ long-term sustainability and essential factors in soil formation and nutrient cycling. The rhizosphere is the region of soil where roots influence microbial activity. The physico-chemical properties of the part create different growing conditions for microorganisms compared to root-free soil. Land-used activities related to residue management practices can considerably impact the size and movement of the soil microbial community and biological properties. Some researchers have reported improvement in microbial activity and population density of bacteria through the incorporation of organic amendments (Van Bruggen and Semenov 2000). Most research has shown increased microbial diversity in soils from organic farming systems compared to conventional farming systems (Shannon et al. 2002; Bowles et al. 2014; Karaca et al., 2011). Organic matter decomposition serves two functions-providing energy for growth and supplying carbon for the formation of new cells.

**Nutrient and Irrigation Water Management in the Cropping System**

Sugarcane being a long-duration crop removes considerable nutrients from the soil. A 100 tonnes of sugarcane crop removes 205 kg N, 55 kg P₂O₅, and 275 kg K₂O besides 30 kg S, 3.5 kg Fe, 1.2 kg Mn and 0.6 kg Zn (Menhi Lal et al. 2000). The micronutrient status of potato-growing areas indicated that zinc is the most deficient micronutrient in potato-growing soils. Imbalanced use of nutrients, besides affecting crop growth and yields, also influence soil physical, chemical, and biological properties adversely. New fertilizer compounds consisting of NPKSZn have also been developed. Sulfur (S) is increasingly recognized as the fourth major plant nutrient after nitrogen, phosphorus, and potassium. The importance of S in agriculture is being increasingly emphasized, and its role in crop production is well recognized (Shukla and Lal 2004, 2007). A shortage in the S supply to the crops lowers the utilization of the available soil nitrogen, thereby increasing nitrate leaching (Lakkineni and Abrol 1994).

Sugarcane is an important crop globally for not only sugar production but also increasingly as a bioenergy crop due to its remarkable dry matter production capacity. It is one of the world’s major C₄ crops that mainly grows in the tropic and subtropics regions. It flourishes under a long, warm growing season with high radiation and adequate moisture incidence, followed by a dry, sunny, and relatively calm but frost-free ripening and harvesting period. Sugarcane crop constitutes 29% of the total world crop production (Gerbens-Leenes and Hoekstra 2011). Globally, it consumes about 220 billion cubic meters (m³) of water annually, which represents 3.4% of the global water use for crop production (OECD/FAO 2018). Average water footprint (WF) of sugarcane as 209–210 m³/t and sugar beet as 132 m³/t. A global average of about 209 m³ of water is needed to produce one ton of sugarcane, indicating that sugarcane crops utilize a substantial amount of water. The WF of sugarcane depends on crop type, growing region, agricultural practice, and climate. The WFs of cane sugar for the major producing countries appear to be 1285 m³/t for Brazil and 1570 m³/t for India (Shukla et al. 2020b). Cane sugar’s weighted global average W.F.s is 1500 m³/t (45% green, 49% blue, 6% grey). The water footprint of sugarcane for northern Thailand is 202 m³/t, and for eastern Thailand, it was found 178.32 m³/t (Kongboon and Sampattagul 2014).

Under different irrigation systems and mulching techniques, the WF of sugarcane production was evaluated. The blue water consumption for sugarcane grown with a thick mulch cover was substantially lower than that produced with a light mulch cover. For subsurface drip-irrigated sugarcane, the blue water footprint was found 8–10 m³/t lower than for center pivot-irrigated sugarcane (Adetoro et al. 2020). Under subsurface drip irrigation with freshwater and treated sewage water studied in sugarcane, Green W.F. in sugarcane was 21, and 26 m³/Mg stems for both irrigated treatments (Barbosa et al. 2017). Also, due to colossal fertilizer and herbicides application in sugarcane practices, high Grey WF resulted in sugarcane systems of Argentina (Jorrat et al. 2018).

All over India, the average quantity of water requirement per tonne of sugarcane was noted at 565.27 m³/t, and...
for Uttar Pradesh, it was 207.81 m³/t. Indian Sugar Mills Association estimated that India’s total water requirement for sugarcane is 80–100 BCM/year (ISMA 2013). Out of this, 80% of the irrigation requirements of sugarcane in India are met through groundwater sources. Thus an average of about 88 kg water/kg of cane and 884 kg of water/kg of sugar for a freshly planted crop, and about 118 kg water/kg of the club or 1157 kg water/kg of sugar for a ratoon crop is required (NABARD 2018).

In the Indian context, regional variation in sugarcane WF is wide, as evident from the analysis done by CACP. Depending on soil texture, soil water holding capacity, atmospheric aridity, and crop growing season, it takes 75–100 L of irrigation water to produce a kg of sugarcane in Bihar compared to 500–800 L required in the states of Maharashtra, Karnataka, and Tamil Nadu. The annual irrigation water requirement of sugarcane in subtropical India is about 1600–2300 mm. However, it ranges from 2000 to 3500 mm in tropical India. Thus, sugarcane requires 6–8 irrigations in the northern part and 30–40 irrigations in the southern part of the country (Shukla et al. 2017b). The majority of the cropped area is irrigated with surface methods for which water use efficiency seldom exceeds 35 percent. Declining water availability for agriculture warrants enhancing the water use efficiency and water productivity in agriculture. Water-saving strategies in sugarcane production systems range from soil mulching to reducing soil evaporation (Pi et al. 2017), adopting drip irrigation to improve irrigation water-use efficiency (Postel et al. 2001), increasing economic returns from each drop of water used (Chai et al. 2016), conservation tilling to sustain soil moisture (Azimzadeh 2012), and adopting different farming systems without hindering the required growing conditions (Schyns and Hoekstra 2014; Davis et al. 2017). Crop diversification also economizes irrigation water use and improves resource use (nutrient use, water use, and weed control) efficiencies. Irrigation during the early phase of the sugarcane crop is applied as per the requirement of the component crop. After harvesting component crop/intercrop, the recommended package of practices for sugarcane is adopted. So with the same amount of water, the component crop completes its life cycle, and the sugarcane crop germinates and enters the tillering phase.

**Weed Smothering Efficiency, Allelopathy of Intercrops on Weeds and Weed Management in Sequential and Intercropping Systems**

Geetha et al. (2019) reported higher weed smothering efficiency in sugarcane + cowpea (36.3%) intercropping system followed by sunn hemp (32.3%) and soybean (32.0%) over the sole sugarcane (control). This was due to the fact that fast growing intercrops often smother the weed population compared with sole crops. It was also reported that intercropping maize with legumes reduced weed density compared with pure stand of maize due to less availability of light for weeds germination and growth and weed smothering efficiency of legumes (Bilalis et al. 2010). Lal and Singh (2004) has also reported that in intercropping of cow pea with spring planted sugarcane effectively suppressed the weed density (81/m²) and reduced the dry weight of weeds significantly (10.1 g/m²) over the sole sugarcane during early growth stages (60 days after planting).

Allelopathy is a biochemical phenomenon with ecological implications involving any harmful or beneficial effect, either direct or indirect, by one plant (donor) on another (target) through the production of chemical compounds that escape into the environment (Rice 1984a, b). Allelochemicals, i.e., the defensive secondary metabolites involved in the allelopathic interactions, can have negative effects on conspecific (autoallelopathy or autotoxicity) and/or heterospecific species (heterotoxicity). They encompass a very wide range of chemical classes, the most representative of which are phenolic compounds (simple phenols, flavonoids, quinones, coumarins, etc.), terpenoids (mono-, di- and triterpenes, sesquiterpenes and steroids) and compounds containing a nitrogen atom (e.g., benzoxazinoids) (Macías et al. 2019). The mechanisms of action of allelochemicals are the most varied, considering that the visible effects on target plants (e.g., inhibition of seed germination, reduction in seedling growth) are often secondary signs of primary changes (inhibition of cell division and elongation, interference with cell membrane permeability, enzymatic activities, respiration and photosynthesis, etc. Scavo et al. (2018). Furthermore, in field conditions, the allelopathic effects are generally caused by the joint action of mixtures of allelochemicals. The role of allelochemicals in acting as biopesticides in agricultural pest management against weeds, insects and diseases has been examined and reviewed (Khanh et al. 2005; Farooq et al. 2011). Various crops from different botanical families show allelopathic properties and can be cultivated alone or in combination with other non-allelopathic crops. Many allelopathic tools can be adopted (crop rotation, intercropping, cover cropping as living or dead mulches, green manuring, use of allelochemical-based bioherbicides). These methods are highly flexible and feature increased efficiency when combined into an integrated weed management strategy. Recent advances in the chemistry of allelopathy are facilitating the use of allelochemicals for bioherbicide production. Besides several biotechnologies, such as stress induction and genetic engineering techniques, can enhance the allelopathic potential of crops or introduce allelopathic traits de novo.
The Brassicaceae family comprises more than 3200 species, of which the Brassica genus includes several highly allelopathic crops such as canola (*Brassica napus* L.), Indian mustard (*B. juncea*), black mustard (*B. nigra*) and cabbage (*B. oleracea*). Rehman et al. (2018) reviewed the use of Brassica allelopathy for weed management and documented that glucosinolates (mainly isothiocyanates and nitriles) and the endogenous steroidal compounds brassinosteroids (e.g., brassinolide, 24-epibrassinolide, 28-homobrassinolide) are responsible for their phytotoxicity. Significant evidence of allelopathic effects has been reported in some leguminous crops. The best known example is alfalfa (*Medicago sativa* L.), commonly used as living or dead mulch for weed management, and widely studied also as a plant model in autoallelopathy (Chon and Kim 2002; Chon et al. 2006). Other examples of allelopathic Fabaceae plants are the bean (*Phaseolus vulgaris* L.), faba bean (*Vicia faba* L.), peanut (*Arachis hypogaea* L.) and, recently, liquorice (*Glycyrrhiza uralensis* L.) and, recently, liquorice (*Glycyrrhiza uralensis* Fisch.) (Li et al. 2014; Ren et al. 2017; Asaduzzaman and Asao 2012). Fabaceae allelopathy is mainly due to phenolic acids such as benzoic, cinnamic, *p*-hydroxybenzoic, vanillic, coumaric, ferulic, caffeic, salicylic.

The Solanaceae family is gaining in interest for the allelopathic potential shown by some important members. Rial et al. (2018), for example, investigated the allelopathic traits of tomato (*Solanum lycopersicum* L.) and identified its major root allelochemicals as the alkaloid-tomatine, the steroidal stigmasterol, the furocoumarin bergapten and the strigolactone solanacol, orobanchol, strigol, etc. Allelopathic crops can be employed to manage weeds in agroecosystems by (i) including them in rotational sequences or (ii) intercropping in close proximity with a cash crop, (iii) cover cropping as living or dead mulches, (iv) crop residue incorporation into the soil and (v) by using their allelochemicals as bioherbicides (Khan et al. 2005; Jabran et al. 2015). The adoption of allelopathy for weed management is highly flexible, varying site to site depending on the specific characteristics of the context: pedo-climatic conditions, weed species, agricultural practices used, economic constraints and farmer’s expectations. Allelopathy can be exploited in different cropping systems, but it certainly plays more beneficial roles in organic farming, and in conservative, minimum and no-tillage agricultural systems, where weed control is often problematic. Moreover, the above mentioned allelopathic weed control tools can be individually applied or combined into an integrated weed management strategy (IWMS) to increase their efficiency (Scavo and Mauromicale 2020).

Sugarcane field residue leachates also reduced the growth of numerous weedy species, such as arrow leaf sida (*Sida rhombifolia* L.) (Sampietro et al. 2007). Three allelopathic compounds, ferulic, vanillic and syringic acids that exhibited allelopathic characteristics have been isolated from sugarcane field residue leachates (Sampietro et al. 2005; Sampietro and Vattuone 2006b). Beggarticks (*Bidens subalternans* L.) and wild mustard (*Brassica campestris* L.) seedling root elongation was reduced due to the presence of phenolic compounds (Sampietro and Vattuone 2006a). Phenolic commercial herbicides are commonly used in production agriculture (i.e., bromoxynil and isonicotin) (Takahashi et al. 2010). Depending on the concentration, sugarcane leachate has either promoted or inhibited growth (Sampietro and Vattuone 2006b). At sugarcane field residue levels typically found in the field, the leachate would inhibit growth, but at a lower 6 g/L concentration the extract promoted root growth of pigweed (*Amaranthus quitensis* L.), radish (*Raphanus sativus* L. var. ‘Sparkler’), sorghum (*Sorghum bicolor* [L.] Moench var. ‘Supergauchazo’), wheat (*Triticum aestivum* L. var. ‘Pegaso’), and wild mustard (*Brassica campestris* L.) (Sampietro and Vattuone 2006b). Rodrigues et al. (2001) documented that the breakdown of sugarcane bagasse lignocellulosic material produced toxic compounds that inhibit cellular growth. Also, leaching or the microbial breakdown of the bagasse may have an allelopathic (toxic) impact on squash plants (Facelli and Pickett 1991; Rice 1984a, b).

Weed management in an intercropping system has always been an issue as concentrated efforts are required to provide weed-free environments at regular intervals to both main crop and component crop for attaining higher productivity levels (Shah et al. 2011). Due to weeds, both in the sole and intercropped sugarcane, reductions in yield have been estimated to the tune of 26–75% (Patil et al. 1991; Singh et al. 2005). Manual and cultural weed control measures are often rendered uncertain due to interference of rains. The use of herbicides is, thus, the only resort as it offers good scope for timely and adequate control of weeds. Application of sulfosulfuron + metsulfuron 30 g/ha in wheat intercropped in sugarcane gave the highest net returns of Rs 83,344/- and a benefit–cost ratio of 1.79. The next profitable alternative was the use of sulfosulfuron 25 g/ha, which led to the net returns of Rs 76,407/- and a benefit–cost ratio of 1.72. A similar benefit–cost ratio was obtained when mesosulfuron + iodosulfuron 21.6 g/ha was applied to control weeds in the sugarcane–wheat cropping system. It was concluded that the productivity of intercropping of wheat in autumn sugarcane could be enhanced effectively by controlling *Rabi* season weeds with the application of sulfosulfuron, sulfosulfuron + metsulfuron, mesosulfuron + iodosulfuron, met sulfuron-methyl, carfentrazone-ethyl, pinoxaden, a dose already recommended to wheat in the subtropical part of India (Kumar et al. 2017).

Few herbicides like trifluralin, pendimethalin and imazethapyr in field peas (Hanson and Thill 2001; Miller...
Trichogramma chilonis, a biocontrol agent— For effective and sustainable sugarcane borer's management, farmers need to keep pest population below a threshold level. Crop rotation is advocated to reduce the sett-borne infection of leaf scald. Removal and destruction of infected plants on the first appearance of disease in case of red rot, smut, GSD and leaf scald are recommended. Treatments of cane setts with fungicides like Bavistin, Mancozeb, Thio Phenate Methyl, etc.; at the time of planting protects the setts in surface-borne pathogens and superficial infection and rotting. Sett treatment with Trichoderma and Pseudomonas have been found quite effective in managing the several pathogens causing severe diseases in sugarcane crops (Shukla et al. 2020a; Goswami et al. 2014; Patel et al. 2019; Widmer 2019). Intercropping of maize and sugarcane has been found effective against termite and enhanced the efficacy of predatory white ants (Silessi et al. 2005). Strip cropping of poplar woods with sugarcane controlled termite (Sattar and Salihah 2002). The benefits of intercropping for controlling aphids and encouraging their natural enemies have also been studied in wheat and rapeseed intercropping systems (Wang et al. 2009).

**Integrated Insect-Pest and Disease Management in Cropping Systems**

Sugarcane is a long-duration crop and infested with a number of insect pests and diseases. The borers and fungal diseases are causes of concern and cause economic damage to the crop. Integration of eco-friendly and cost-effective approaches are required for managing insect pests and plant pathogenic population below a threshold level. Usually, insect-pests and disease-tolerant sugarcane varieties are recommended. Healthy looking seed cane material is advised for cane planting. Crop rotation is advocated to farmers to keep pest population below a threshold level. For effective and sustainable sugarcane borer’s management, a biocontrol agent—Trichogramma chilonis has been found effective. It is an egg parasitoid and multiplied and released against larval parasitoids like Cotesia flavipes, Isotima javensis, etc. Some granulosis viruses and mud cardine fungi like Metarhizium anisopliae are used in the management of sugarcane insect pests (Shukla et al. 2019). Staggered planting, soil solarization, and summer plowing have also been found to control soil-borne diseases and insect pests. Treatment of cane in Moist Hot Air (MHAT) at 54 °C and 95–99% R.H. for 2.30 h eradicates sett borne infection of red rot pathogen (80%), ratoon stunting disease, grassy shoot disease and smut (99–100%). This also reduces the sett-borne infection of leaf scald. Removal and destruction of infected plants on the first appearance of disease in case of red rot, smut, GSD and leaf scald are recommended. Treatments of cane setts with fungicides like Bavistin, Mancozeb, Thio Phenate Methyl, etc.; at the time of planting protects the setts in surface-borne pathogens and superficial infection and rotting. Sett treatment with Trichoderma and Pseudomonas have been found quite effective in managing the several pathogens causing severe diseases in sugarcane crops (Shukla et al. 2020a; Goswami et al. 2014; Patel et al. 2019; Widmer 2019). Intercropping of maize and sugarcane has been found effective against termite and enhanced the efficacy of predatory white ants (Silessi et al. 2005). Strip cropping of poplar woods with sugarcane controlled termite (Sattar and Salihah 2002). The benefits of intercropping for controlling aphids and encouraging their natural enemies have also been studied in wheat and rapeseed intercropping systems (Wang et al. 2009).

**Sugarcane Based Integrated Farming System (IFS)**

Integrated farming system approach involving crop, livestock, fisheries options could improve farmers’ profit besides employment generation of rural people. Recycling of bye products and co-products of other enterprises influences the viability and farmers’ profitability of the system. At the IISR Lucknow, sugarcane-based IFS models for marginal and small farmers had been developed for improving yield and income (IISR 2020; Dwivedi et al. 2020). The IFS is one of the essential principles for achieving the goal of higher yields of different component crops and enterprises, livelihood security, soil health management, nutritional security, by-product recycling, eco-friendly agri-system, employment generation throughout the year by adopting principles of the sustainable agriculture. At the IISR Lucknow, the field experiments on autumn and spring sugarcane-based systems consisting of different components of agriculture (Sugarcane), viz. horticulture (vegetables, banana, papaya, and boundary planting of around Christ’s thorn), Backyard Poultry, Fisheries, Vermicompost, Apiculture, Mushroom was taken up. Allocation of farmland to each component was kept in such a way that may fulfill the minimum essential annual requirements of food, vegetables, fish, egg, chicken, honey, pickles, mushrooms etc., of a household having seven family members and overall improvement in their livelihood. Impacts of different treatments on yield, profitability, employment generation, product (waste) recycling parameters were observed. The results indicated that autumn sugarcane-based integrated farming system as Sugarcane + Vegetables (Garlic, Fenugreek, Coriander, Tomato, Cauliflower, Spinach, Carrot, Fababean, Onion, Brinjal, Green chili, Cabbage, Pea, Soya, Sauf, bottle guard, okra, cowpea, cucurbit, maize) + Horticultural Crop (Karonda boundary plantation + papaya + banana) + Backyard Poultry (Breed, Asheel, Nirbheek, Kadaknath, Quail) + Fisheries (Rohu, Catla,
Nain) + Vermicompost (Erucina fotida) + Apiculture + Mushroom fetched net income Rs. 462,412/ha and fetched additional income of Rs. 203,212/ha with B: C ratio of 3.27. However, spring sugarcane-based integrated farming system as sugarcane + vegetables (bottle gourd, sponge gourd, tomato, brinjal, pumpkin, onion, maize fenugreek, pachoi, Chinese gobi) + Horticultural Crop (banana, karonda, papaya) + backyard poultry (Breed-Asheel, Nirbheek, Kadaknath, Quail) + Fisheries (Rohu, Catla, Nain) + Vermicompost (Erucina fotida) + Apiculture + Mushroom fetched net income of Rs. 453,350/ha and additional income of Rs. 197,550/ha with a B: C ratio of 3.43 (Table 9). However, sole planting of sugarcane could result in a B: C ratio of 2.57 and 2.60 during autumn and spring planting conditions, respectively (Table 9-IISR 2020).

**Summary and Conclusions**

Sugarcane crop generates about 10–12 t/ha trash (dry crop residues) annually. Trash mulching in subsequent ratoon crops conserves soil moisture, controls weed growth, and enhances soil organic carbon after decomposition. Thus integrated nutrient management involving organic, inorganic sources, biofertilizers, green manuring, etc., holds great promise in sustaining soil fertility and crop productivity in sugarcane-based systems. In this series, intercropping of mustard with autumn sugarcane has also been found an economically viable option compared to the mustard-sugarcane sequential system. Weed management in sugarcane has also been found to be a critical issue during 90–120 days after planting. Intercropping also controls weed growth and can minimize chemicals besides economizing other inputs.

Simultaneous planting of sugarcane and wheat in November–December opened new avenues to increase sugarcane productivity without affecting the yield of the wheat crop. A new system of FIRBS (Furrow Irrigated Raised Bed System) has also been introduced to improve sugarcane and wheat yields. Adopting early maturing sugarcane varieties also plays a significant role in improving sugar recovery. In irrigated agroecosystem, there is an excellent scope of the increasing area under pulse crops through crop diversification/intensification besides improving their productivity. Resource use efficiencies (nitrogen use efficiency, weed control efficiency, water use efficiency, etc.) and land equivalent ratio could be improved through intercropping pulse crops with sugarcane. Crop residues recycling of pulses addresses the vital issue of decreasing soil organic carbon created due to indiscriminate/imbalanced use of fertilizers and lower use/unavailability of organic manures. Sugarcane growers can take advantage of this and grow various short-duration crops like cereals, pulses, vegetables, and spices as intercrops to obtain an interim return.

Growing oilseed crops such as mustard and rapeseed (toria) with autumn planted sugarcane in subtropical India is very common to improve the land-use efficiency and crop equivalent yields. Among dual-purpose legumes, the highest net monetary return was worked out for the spring sugarcane + green gram system followed by sugarcane + cowpea. Introducing early-bulking high-density intercrops (Egyptian clover, Persian clover, and Indian clover) can mitigate the problems associated with winter-initiated ratoon. Furrow Irrigated Raised Bed (FIRB) system of wheat sowing saves 25–30% water and facilitate mechanical weeding. Including high-value medicinal and aromatic crops is also a viable option in an intercropping system with sugarcane. At the IISR, Lucknow, sequential cropping with wild marigold recorded the highest wheat equivalent yield. Crop diversification improves water productivity and farmers’ profitability. Crop diversification also improves resource use (nutrient use, water use, and weed control) efficiencies. The higher weed smothering efficiency in sugarcane + cowpea intercropping system

**Table 9** Integrated farming systems influencing economics with autumn and spring-planted sugarcane. *Source:* IISR (2020)

| Cropping/Farming systems | Autumn sugarcane | Spring sugarcane |
|--------------------------|------------------|------------------|
|                          | Cost of production (Rs/ha.) | Gross income (Rs/ha.) | Net income (Rs/ha.) | B:C ratio | Cost of production (Rs/ha.) | Gross income (Rs/ha.) | Net income (Rs/ha.) | B:C ratio |
| Sugarcane (Sole) CoPk05191 | 165,000 | 424,200 | 259,200 | 2.57 | 160,000 | 415,800 | 255,800 | 2.60 |
| Sugarcane + Vegetables (including horti.crops) throughout year | 185,450 | 509,552 | 324,102 | 2.75 | 172,480 | 497,520 | 325,040 | 2.88 |
| Sugarcane + Vegetables (including horti.crops) throughout year + Backyard poultry | 195,450 | 552,312 | 356,862 | 2.83 | 182,480 | 540,280 | 357,800 | 2.96 |
| Sugarcane + Vegetables throughout year (including horti.crops) + Backyard poultry + Fisheries + Vermicompost + Apiculture + Mushroom | 203,900 | 666,312 | 462,412 | 3.27 | 190,930 | 654,280 | 453,350 | 3.43 |
was recorded in tropical India. The role of allelochemicals in acting as biopesticides in agricultural pest management against weeds, insects and diseases has been examined and reviewed. Weed management in an intercropping system has always been an issue as concentrated efforts are required to provide weed-free environments at regular intervals to both main crop and component crop for attaining higher productivity levels. Recycling of bye products and co-products of other enterprises influences the viability and farmers’ profitability of the system. Sugarcane crop is not exhaustive rather than soil fertility restorer, if the crop products/by-products are being managed well in soil–sugarcane—sugar production system. Trash, press mud cake, vinasse, composted bagasse, rhizodeposition of stubble play a significant role in sustaining soil fertility and increasing crop productivity. Integrated farming system approach involving crop, livestock, fisheries options could improve farm profit particularly for marginal and small farmers besides employment generation of rural people.

**Future Thrusts**

1. Technology for high density cane farming through appropriate agronomy vis-a-vis enhancing crop productivity and profitability of sugarcane planted under wide row spacing along with high value intercrops is required.

2. Synchronizing nutrient supply with crop demand under drip fertigation for upscaling nutrient use efficiency in sugarcane (plant)-ratoon system is required to improve the resource use efficiencies.

3. Management of bio-resources for enhancing sugarcane productivity and soil health and scientific aids for site specific nutrient management through variable mapping of soil properties in sugarcane growing soils need to be developed.

4. Emphasis on research on nanofertilizers for increasing N use efficiency besides sustaining soil organic carbon through crop residue management along with microbial consortia is required to reduce the chemical fertilizers in sugarcane based system.

5. Sugarcane based integrated farming system models for small farm holders are required to be developed and evaluated in different growing zones to meet the multiple needs of farmers, mid-season income generation and reduce the cost of production besides sustaining soil fertility.

**Declarations**

**Conflict of interest** Authors declare that there is no conflict of interest.

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