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The Sweet Gains of Diversification: A Review of Intercropping Benefits in Sugarcane Farming

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ABSTRACT

Sugarcane farming, a cornerstone of the global sugar and bioenergy industries, has seen a surge in interest in recent years due to the adoption of sustainable agricultural practices. One such practice, intercropping, is becoming increasingly recognized for its potential to transform the dynamics of sugarcane cultivation. As the world grapples with the challenges of sustainable agriculture and food security, the adoption of intercropping in sugarcane farming stands as a promising strategy. This review emphasizes the pivotal role of diversification in enhancing the resilience and prosperity of sugarcane farming while contributing to global agricultural sustainability. It underscores the pivotal role of intercropping in sugarcane cultivation, not only in augmenting crop yields and farmer livelihoods but also in fostering soil resilience and health.

Key words: Diversification, Intercropping, Soil health, Sugarcane.

For a long time, farmers, researchers and policymakers worldwide have consistently focused on the development of self-sustaining, low-input and energy-efficient agricultural systems within the framework of sustainable agriculture (Altieri *et al*., 1983; Altieri, 1999). Nevertheless, the majority of contemporary agricultural practices, such as mechanization, monoculture cultivation, the adoption of high-yield crop varieties and the extensive use of agrochemicals for fertilization and pest control, have resulted in a simplification of the various elements within agricultural systems. This simplification has, in turn, resulted in a significant loss of biodiversity (Lulie, 2017). In contrast, the concept of on-farm biodiversity is well-recognized among traditional farmers, particularly in developing countries. Traditional farming systems in these regions are notable for their substantial genetic diversity, which is evident through practices such as mixed cropping and agroforestry. These systems rely on a multitude of varieties of domesticated crop species and their wild counterparts (Altieri, 1999). In the majority of multiple cropping systems practiced by small-scale farmers, the productivity, as measured by the amount of harvestable products per unit of land, tends to be greater than that of sole cropping under similar management conditions. This enhanced productivity is a result of reduced pest and disease occurrences, soil conservation and a more efficient utilization of nutrients, water and solar radiation (Lulie, 2017).

Intercropping can be described as a farming technique where two or more different crops are cultivated together in a single field during a single growing season. It serves as a method to enhance diversity within the agricultural environment. By adopting intercropping, farmers can promote ecological equilibrium, make more efficient use of available resources, boost both the quantity and quality of their yields and decrease the negative impact of pests, diseases and weeds on their crops (Mousavi and Eskandari, 2011). In addition, intercropping helps in land use optimization, soil health improvement, water conservation, risk mitigation and improved farm resilience.

Sugarcane presents a unique opportunity for intercropping. It is typically planted in wide rows and takes several months to form a full canopy. During this period, the space between the rows sees underutilized soil, solar energy and a significant portion of rainfall. Therefore, any crop that matures and can be harvested within 90-120 days before the sugarcane canopy forms can be planted in these interrow spaces (Parsons, 2003). Currently, the economic returns from sugarcane are lower than those from the rice-wheat system and this reduced income due to decreased cropping intensity can be offset by intensifying the sugarcane-based production system. This intensification can be achieved through diversification in terms of both space and time, allowing cane farmers to meet multiple needs while also preserving long-term soil health (Kaur *et al*., 2015). There are abundant possibilities for intercropping sugarcane with short duration, higher-value crops that generate income during the mid-season and contribute to household nutrition and economic stability (Singh *et al*., 2008).

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Pulses, owing to their diverse characteristics in terms of growth duration, adaptability to various climates and their nitrogen-fixing abilities, are an essential component of various cropping systems in the country, including those involving sugarcane. Pulses play a valuable role by providing nitrogen supplementation, aiding in weed suppression, enhancing soil quality and supporting the sustainability of the plant ratoon system in sugarcane cultivation (Shukla *et al*., 2017). According to Viaud *et al*. (2023), consolidation of sugarcane-legume intercropping is a promising practice to reduce herbicide use, minimize requirements of nitrogen fertilization and reduce N_2O emissions. Despite an average decrease in yield in the sugarcane-legume intercropping system by 3.34% compared to monocropping, inclusion of legumes into the system is a viable option as these are less damaging than weeds for sugarcane. A study conducted by Nadeem *et al*. (2020) showed that intercropping lentil in between the sugarcane crop resulted in significant variation in growth and yield attributes of cane. Among various treatments, sugarcane planted alone in 120 cm trench recorded maximum leaf area index (8.97), leaf area duration (1346 days), crop growth rate (12.42 g m^{-2} day^{-1}), net assimilation rate (3.15 g m^{-2} day^{-1}) and total dry matter (34.64 t ha^{-1}). A similar trend was observed in ratoon crop too. This can be attributed to the increased availability of space and nutrients, lesser competition and better growth of cane shoot and root system when planted alone, in comparison to cane-lentil intercropped system. Compared to other planting patterns (45/60/75/90 cm pits with 90 cm diameter, 60 and 90 cm double rows planting) stripped cane yield (SCY) (153.10 and 154.36 t ha^{-1}) and total sugar yield (TSY) (20.50 and 20.62 t ha^{-1}), with and without lentil intercropping, respectively, were significantly higher in 120 cm trench planting. Intercropping of sugarcane with horticultural crops, *viz*. okra, tomato and watermelon, leads to effective utilization of resources and reduction in labour costs for weed management in early growth stages of cane (Gana and Busari, 2003).

As researchers and agricultural experts strive to develop more environmentally friendly and economically viable agricultural systems, the study of intercropping in sugarcane has provided valuable insights into its benefits and practical applications. The findings of various researchers who have explored intercropping in autumn and spring-planted sugarcane with pulses, high value medicinal crops, vegetables and oilseed crops are as follows.

Intercropping in autumn planted sugarcane

An investigation was carried out to analyse the profitability of inclusion of various winter vegetables as intercrops in autumn planted sugarcane. Cauliflower, cabbage, knol khol, turnip, carrot, radish and potato were selected as intercrops for sugarcane planted in 90 cm apart furrows. The number of tillers and millable canes were significantly higher with cane+potato system, as compared to other combinations. Intercropping with potato also increased the cane yield by 8.25%. The practices like deep hoeing of the field for ridge planting, earthing up and digging of tubers might have attributed to improved soil aeration and weed free conditions. The cane did not perform better under intercropping with root vegetables (carrot and radish). However, it was found that intercropping of autumn sugarcane with winter vegetables helped in effective utilization of resources in comparison to sole crop of cane and thus generated higher economic returns (Singh *et al*., 2008b). Govinden (1990) reported that sugarcane-potato intercropping system generates 22% more total edible energy and 63% higher net returns than from sole cropping of sugarcane and thus, is undoubtedly a popular sugarcane-based system in Mauritius to a large extent. Hossain *et al*. (2007) revealed that growing three different green manure crops namely, *dhaincha*, sunhemp and indigo as second intercrop in sugarcane (after the harvest of potato) followed by incorporation significantly increased the number of tillers, number of millable canes (NMC), cane height, cane girth, number of internodes and cane yield over the control plots. Highest cane yield was obtained for the treatment sugarcane+potato+ *dhaincha* (124.5 t ha^{-1}), while the lowest for sugarcane+potato (109.6 t ha^{-1}). These were in accordance with findings of Paul *et al*. (1999).

Rehman *et al*. (2014) concluded that adoption of sugarcane+potato system generates higher net returns and benefit cost ratio, over the cane intercropping with wheat, gram and soybean. This was in agreement with the results of Verma *et al.* (1985). Based on a study by Kumar *et al.* (2011) in autumn planted sugarcane under valley conditions of Uttarakhand, the sugarcane+onion and sugarcane+potato intercropping systems were found to perform better in terms of the cane equivalent yield and net returns. The reduction in cane yield was the lowest in sugarcane+potato (1.5%), while the highest in sugarcane+french bean (12.8%) system. Among the various intercropping systems with winter vegetables as intercrops, sugarcane+fenugreek proved to be least remunerative. According to Imam *et al*. (1990) significantly greater net benefits than sole cropping can be derived, through intercropping sugarcane with high value crops like onion, garlic and potato. A good level of temporal complementarity exists between sugarcane and potato during winter, when the growth of sugarcane is slow and potato grow quickly. These were in accordance with the results of the study by Nankar (1990).

The results of a trial conducted by Khippal *et al.* (2016) showed that autumn planted sugarcane can be successfully intercropped with pea, chickpea, lentil and *raya* for achieving higher net returns and improving soil health. Total Area Time Equivalent ratio (ATERt) values were 22-28% higher with all the intercropping systems in comparison to sole cropping, with maximum advantage from sugarcane+ chickpea. The production potential and

economic viability of autumn sugarcane-based intercropping systems were assessed by Singh *et al.* (2008a). Intercropping the plant crop with *rajmash* resulted in maximum cane yield and net returns. While the performance of ratoon crop initiated from sugarcane+lentil system gave significantly higher cane length, cane girth, cane weight, NMC and cane yield. The yield and yield attributes of ratoon cane initiated from plant crop intercropped with oilseeds (Indian mustard and rapeseed) and cereal (maize) did not perform well. Yadav and Prasad (1990) opined that intercropping of autumn planted sugarcane with french bean in 1:2 (sugarcane: beans) row arrangements with application of 80 kg N ha^{-1} resulted in optimum beans yield. However, increased competition for resources and shading effect of intercrops adversely affected the cane shoot density.

Intercropping of autumn planted sugarcane with medicinal and high value *rabi* crops like celery, *gobhi sarson* and radish were found to increase the net returns by 10.1 to 31.8% compared to sole crop of sugarcane. However, intercropping with barley adversely affected sugarcane by reducing the tillering to a tune of 24.4%. Sugarcane+gobhi sarson 'GSL2' (1:1) recorded highest cane equivalent yield (87.95 t ha^{-1}) among all other combinations (Kumar *et al*., 2015). In a study by Singh and Vashist (2004), the sole cropping of autumn sugarcane was found to give maximum cane yield (593.2 q ha^{-1}) which was at par with cane yield obtained from sugarcane: onion (588.1 q ha^{-1}) planting in 1:1 row ratio.

Significantly higher NMC (120.9 thousand ha^{-1}) and cane yield (75.7 t ha^{-1}) were recorded under autumn planted sugarcane+amaranthus (2:2) intercropping system in comparison to 1:1 row ratio intercropping system (115.2 thousand ha^{-1} and 71.3 t ha^{-1}, respectively). Amaranthus crop sown in autumn takes advantage of the slow germination and growth of sugarcane during the months of December and January in north Indian conditions and grows very fast resulting in high biomass production (Singh *et al*., 2009). Saini *et al.* (2003) proposed that intercropping with winter vegetables has an antagonistic effect on the productivity of sugarcane. The cane yield was decreased by 5.1, 7.4 and 11.5% with intercropping of radish, turnip and *palak*, respectively, over pure cane. Whereas, interplanting of peas in autumn sugarcane gave higher cane yield (75.3 t ha^{-1}), cane equivalent yield (103.4 t ha^{-1}) and net profit (Rs. 26,785 ha^{-1}). On contrary to this, intercropping of winter vegetables-potato, cauliflower, knol-khol, cabbage, turnip, carrot and radish, had a beneficiary influence due to efficient utilization of resources as compared to sole cane crop (Singh *et al*., 2018).

Among the various intercropping combinations tried, autumn sugarcane+maize system resulted in maximum mean cane equivalent yield (200.6 t ha^{-1}) and highest net returns (Rs 1,24,874 ha^{-1}). Additional yield from maize without sugarcane being adversely affected and good price of maize cobs in the market could be the reasons for this. Similar results were given by Singh and Chaudhary (1996). The shoot height at maximum tillering stage and cane weight at harvest were superior in crop intercropped with lentil owing to no shading effect of the intercrop and increased nitrogen fixation for growth and development of canes. The cane yield declined with all the intercrops, except maize, to the tune of 8.7%, 14.8% and 13.3% for lentil, mustard and *rajmash*, respectively (Rana *et al*., 2006).

Based on a study conducted by Shukla and Pandey (1999) it was concluded that intercropping sugarcane with different mustard genotypes reduced the cane yield by 13.8%, due to competition for nutrients, moisture, light and space. Nevertheless, cane equivalent yield was increased through intercropping by 14%. Sugarcane+mustard 'Bio 417' (1:1) generated highest cane equivalent yield (99.75 t ha^{-1}) and commercial cane sugar equivalent yield (13.11 t ha^{-1}). The combination of sugarcane with Indian mustard and sugarcane with oilseed rape systems generated extra income ranging from USD 535 to USD 1229 per hectare compared to cultivating sugarcane alone. This suggests that both oilseed rape and Indian mustard are viable options for intercropping with autumn sugarcane, as they can substantially increase the overall income from the land. Intercropping sugarcane with Indian mustard and oilseed rape did not exhibit a significant impact on cane yield. However, when considering the combined yield of sugarcane and the intercrop, the sugarcane-Indian mustard system yielded the highest cane equivalent yield, ranging from 104.4 to 121.4 t ha^{-1}. This was notably higher than the cane equivalent yield of the sugarcane-oilseed rape system, which ranged from 90.0 to 103.7 t ha^{-1}. Importantly, both intercropping systems produced higher cane equivalent yields when compared to growing sugarcane alone in two consecutive years (Kaur *et al*., 2016). An experiment conducted by Khan *et al.* (2012) included sole sugarcane, sugarcane intercropped with one, two and three rows of canola and sole canola cropping as treatments. The results showed that the biological cane yield (164 t ha^{-1}) and stripped cane yield (102.2 t ha^{-1}) were significantly higher for sole cropped sugarcane compared to the other treatments. On the other hand, two rows sugarcane strips planted with single row of canola produced maximum biological (136.77 t ha^{-1}) as well as stripped cane yield (89.02 t ha^{-1}). However, the cane quality parameters were not affected by the treatments. Similar results were reported by Al-Azad and Alam (2004). They revealed that sole planting of sugarcane is more profitable than intercropping cane with potato, onion, coriander, mustard and garlic.

On the contrary, findings of study carried out by Rasool *et al*. (2011) revealed that sole cropping of sugarcane is more profitable than intercropping of *rabi* crops (wheat, lentil and gram) in between autumn sugarcane. The NMC, cane length, cane diameter and cane yield were significantly higher in sugarcane planted alone. This decrease in yield with inclusion of intercrops might be due to the competition

of intercrops with cane for growth resources during cane formation and growth stages. Among the intercrops, sugarcane-lentil system gave higher economic returns.

Intercropping in spring and *suru* planted sugarcane

An experiment was conducted to evaluate the influence of intercropped dual-purpose legumes in spring sugarcane plant-ratoon system by Singh *et al*. (2005). The cane yield obtained from sole cropping of sugarcane (73.52 t ha^{-1}) was significantly at par with that of the cane yields from sugarcane+*dhaincha* and sugarcane+green gram system (72.18 and 68.49 t ha^{-1}, respectively). On the other hand, sugarcane+cowpea intercropping system recorded significantly higher cane equivalent yield (80.3 t ha^{-1}), sugar equivalent yield (9.47 t ha^{-1}), net monetary returns (Rs 33,341 ha^{-1}) and nitrogen addition (71.6 kg ha^{-1}) to the soil once the green biomass of cowpea was incorporated. Verma *et al.* (2020) also reported a remarkable increase in the system productivity and net returns with urdbean and moongbean as intercrops in the spring planted sugarcane. Kumar *et al.* (2006) based on an investigation in spring sugarcane system indicated that sole sugarcane gave highest cane yield (101 t ha^{-1}), which was at par with sugarcane+ *Sesbania* intercropping system (93.6 t ha^{-1}). Among various intercrops grown, *Sesbania* with sugarcane produced maximum NMC, cane weight and commercial cane sugar yield. However, sugarcane + cowpea system generated 17.2%, 26.5%, 19.0% and 15.8% higher mean cane-equivalent yield (118.4 t ha^{-1}) than sole sugarcane, sugarcane + *Sesbania*, sugarcane + urdbean and sugarcane + mungbean intercropping system, respectively.

Among different systems, intercropping of field bean, *palak* and green gram produced cane yields (103.9 t ha^{-1}, 98.4 t ha^{-1} and 100.5 t ha^{-1}, respectively) significantly at par with pure stand of sugarcane (104.8 t ha^{-1}). While, lowest cane yields were recorded in sugarcane intercropped with watermelon, muskmelon, cucumber, ridge gourd and tomato (Gouri *et al*., 2015). Prakash *et al*. (2009) revealed that marigold (*Pusa Narangi*) interplanting in spring sugarcane elevated the cane yield, intercrop flower yield, additional income and organic matter content of the soil.

The performance of spring planted sugarcane with mint species as intercrop was evaluated by Kothari *et al*. (1987). The cane yield was reduced to the extent of 17.8%, 18.1% and 30.7% with intercropping of bergamot mint, pepper mint and spear mint, respectively. In a similar study by Singh *et al*. (2000), intercropping sugarcane with one row of *Mentha* species didn't have a significant impact on cane yield, while having two rows of *Mentha* species led to a decrease in yield. Among the mint varieties, spearmint had the most pronounced negative effect on sugarcane yield, while bergamot mint had the least impact. Kothari and Singh (2004) revealed that intercropping sugarcane with mint in paired row planting did not result in a decrease in cane yield. However, menthol mint and spearmint experienced a substantial reduction in yield, ranging from 52% to 75%, compared to their sole crop yields. Nevertheless, intercropping mint with sugarcane, specifically with the Co-Lk 8001 variety, significantly enhanced land use efficiency by 23% to 35%, gross returns by 29% to 46%, net returns by 90% to 137% and the benefit-cost ratio by 44% to 63%.

Vashist *et al*. (2003) based on intercropping studies in spring planted sugarcane under flood plain conditions suggested that vegetables such as cabbage, onion, bell pepper, summer squash and tomato can be grown successfully to make the spring planted sugarcane more profitable. Lowest reduction in cane yield were caused by bell pepper and cabbage. Maximum cane equivalent yield was recorded under cane + summer squash (2,638 q ha^{-1}) followed by cane + bell pepper (1,740 q ha^{-1}) systems. Kumar *et al.* (1990), based on an experiment conducted in Karnal reported that intercropping spring sugarcane with vegetables such as okra, cowpea, tomato, guar and *tinda* (*Citrullus lanatus*) decreased the cane yield by 22.3, 19.3, 15.8, 12.8 and 4.4%, respectively. Based on an investigation carried out by Zarekar *et al.* (2018) under lateritic soil of Konkan region to study the effect of planting methods and intercropping on productivity of sugarcane planted in *suru* season, it was concluded that paired row planted sugarcane intercropped with green gram recorded highest cane yield (89.03 t ha^{-1}), NMC (78251.67), green top yield (11.66 t ha^{-1}), trash yield (9.15 t ha^{-1}) and maximum nutrient uptake (198.93 kg N ha^{-1}, 15.17 kg P_2O_5 ha^{-1}, 289.47 kg K_2O ha^{-1}). The combination of paired row planted sugarcane intercropped with sweet corn was found to be more remunerative, compared to cabbage, groundnut, amaranthus and green gram.

The performance of *suru* sugarcane under different intercropping systems and planting methods was studied by Jadhav *et al*. (2022). The cane height, cane girth, number of internodes per cane, NMC, cane yield and green top yield were superior for paired row planted sugarcane intercropped with 3 rows of green gram sown at 30 cm spacing in between paired rows. Significantly higher cane equivalent yield was recorded when paired row planted sugarcane was intercropped with 2 rows of sweet corn at 45 cm spacing in between paired row, followed by sugarcane intercropped with cabbage. With the intercropping of groundnut in *suru* sugarcane, the cane yield decreased by 4.89%. However, the cane yield remarkably increased by 12.88% with groundnut intercropping (131.61 t ha^{-1}) over sole cropping of sugarcane (116.59 t ha^{-1}) (Ombase *et al*., 2017). Higher net returns were achieved through intercropping with summer groundnut in *suru* sugarcane (Shinde *et al*., 1990).

Effect of sugarcane-based intercropping on soil health

Solanki *et al.* (2020) investigated the impact of sugarcane-legume intercropping on soil diazotrophic microbiome and they concluded that the soil microbial activity was positively

improved with legume intercropping. Among the three cultivation systems studied, namely, sugarcane monoculture, peanut-sugarcane intercropping and soybean-sugarcane intercropping, maximum percentage of overlapped taxonomic units were observed under soybean –sugarcane intercropping. In addition to tremendously increasing the cane growth parameters, sugarcane+peanut system showed a beneficiary effect on the soil rhizospheric activity, with significant proliferation of bacteria belonging to genera *Devosia*, *Rhizobiales*, *Myxococcales*, *Allorhizobium-Neorhizobium-Pararhizobium-Rhizobium*, *Bradyrhizobium* and *Sphingomonas* (Pang *et al*., 2022). Tang *et al.* (2021) also reported similar results based on their study on sugarcane-peanut intercropping system. Lian *et al*. (2018) found that sugarcane intercropping with soybean in acid soils of South China increased the abundance of important fungal genera, such as *Trichoderma*, *Hypocreales* and *Fusarium*, whereas decreased the relative abundance of *Gibberella* and *Chaetomium*, which were closely associated with soil parameters- organic matter content, pH, total nitrogen and nitrate in soil. A study by Solanki *et al*. (2017) concluded that soybean intercropping with sugarcane boosted the soil microbial activity and enhanced the diversity of nitrogen fixers, like *Brevibacterium*, *Burkholderia*, *Delfti*a, *Leucobacter*, *Pseudomonas*, *Sinorhizobium* and *Variovorax*, in soil.

Intercropping sugarcane with pulse crops, such as, green gram, lentil, *rajmash* and cowpea resulted in significant increase in nitrogen (N) mineralization by 34%, 29%, 24% and 22%, respectively. However, N mineralization was comparatively lesser with wheat, maize, mustard and potato as intercrops. The residues of labile carbon substrates like pulses are easily decomposable and promote N mineralization, which are indicated by the narrow CO_2-C/N mineralized ratio for pulses (Suman *et al*., 2006).

The soil physico-chemical properties improved under sugarcane+lentil intercropping system compared to sole sugarcane. The inclusion of leguminous crops in the system added organic matter to the soil and the fibrous root system made the soil porous, thus reducing the bulk density (1.26 g cm^{-3}) and increasing the infiltration rate (4.75 mm h^{-1}) (Singh *et al*., 2008). In an experiment soybean and velvet bean (*Mucuna pruriens*) were selected as intercrops in sugarcane field. The results of the study indicated that the effects of intercropping on soil organic carbon, readily oxidized organic carbon, dissolved organic carbon and aggregates stability of soil, plant water content and nutrient (N, P and K) content were beneficial. However, the yield obtained was higher in monocropping treatment than the intercropped plots, which can be attributed to the competition for resources (Hu *et al*., 2022).

Singh *et al*. (2021) concluded that intercropping sugarcane with mustard or potato is an efficient way to improve functional diversity, soil quality and crop productivity. The sugarcane+mustard-ratoon-cowpea system helped to achieve higher soil microbial counts, microbial biomass carbon and nitrogen, basal soil respiration, soil enzyme activity, total carbon and nitrogen, available nitrogen, zinc, copper, iron and cation exchange capacity (CEC). Hence, the functional diversity indices and soil quality index were significantly increased.

The sugarcane/soybean intercropping with reduced nitrogen input improved crop productivity while lowering the carbon footprint (CF) of sugarcane fields in China. The CF values of the unit yield for sugarcane/soybean intercropping were 3.2%-30.4% lesser than those of the sole cropping systems and thus contributed to cleaner production in an agricultural system (Wang *et al*., 2020). In a study conducted by Kumar *et al.* (2014) in western Uttar Pradesh, the farmer's practice of raising autumn sugarcane and wheat in sequence was compared with two other treatments- intercropping sugarcane with mustard and with onion. It was observed that onion intercropped in sugarcane raised the soil organic matter content, over the other two practices, as a result of the addition of decomposing onion-based residues to the field.

Nutrient management in sugarcane based intercropping system

Singh *et al*. (2005), based on a study conducted at IISR, Lucknow indicated that there was a significant increase in the NMC, cane yield and cane equivalent yield with increasing levels of N from 0 to 150 kg ha^{-1} and the cane juice quality was not adversely affected by higher N application, even up to 150 kg ha^{-1}. It was observed that maximum intercrop yield (19.6 q ha^{-1}), cane equivalent yield (96.8 t ha^{-1}), net returns (Rs.37,641 ha^{-1}) and benefit cost ratio (1.42) were recorded with intercropping system of sugarcane+ cowpea at the highest nitrogen dose of 150 kg ha^{-1}.

Highest system productivity and profitability could be achieved through intercropping of two rows of grain amaranth in autumn sugarcane planted in paired rows (45:135 cm) with 150% recommended dose of fertilizers (RDF). However, 125 and 150% RDF were found to be equally advantageous on the basis of LER values. The total plant nutrient uptake was found to increase with an increase in fertilizer doses for component crops up to 150% RDF (Singh *et al*., 2009).

The effect of intercropping of toria/yellow mustard *(*one and two rows) with sugarcane on nematode population and yield of crop was studied. Maximum cane equivalent yield was recorded with sugarcane + yellow mustard (one row) intercropping system (76.22 t ha^{-1}), followed by sugarcane + yellow mustard (2 rows) (73.75 t ha^{-1}). Increase in nitrogen level from 120 to 180 kg ha^{-1} increased cane yield, intercrop yield as well as nematode population as a result of increased root volume (Haidar *et al*., 2004).

The nitrogen fertilizer application was found to increase the number of tillers and the yield parameters including NMC, cane length, cane girth and cane weight in plant

sugarcane crop in mustard or wheat rotations. The following first sugarcane ratoon also showed a similar trend. The cane yields of plant crops were increased from 52.8 to 66.2 t ha^{-1} and from 46.1 to 63.6 t ha^{-1} in mustard/sugarcane and wheat/sugarcane rotation, respectively, as the N application rates increased from 0 to 150 kg ha^{-1}. The residues from the intercropped green manure crop, *Sesbania aculeate,* increased the yield of the following sugarcane ratoon crop by 9-10% (Yadav and Yaduvanshi, 2001). Ullah *et al.* (2018) evaluated the performance of sugarcane-sugarbeet intercropping system under varying levels of fertilizers. With each increment of NPK level, the yield attributes of the crops, including NMC and beets m^{-2}, stripped cane and beet root weight, stripped cane and beet yield and sugar yield and recovery were significantly enhanced. A dose of 250 kg NPK ha^{-1} was most appropriate with respect to yield and economic returns from cane. However, significantly higher single root weight, crop and sugar yield of sugarbeet were obtained with 300 kg NPK ha^{-1} as compared to that from 250 kg NPK ha^{-1}.

Weed management in sugarcane based intercropping system

Interplanting various crops alongside sugarcane did not exhibit substantial weed control benefits in comparison to growing sugarcane alone, except for peas, which demonstrated a noteworthy decrease in weed biomass at 105 DAS during 2010-2011 and at 70 DAS during 2011-2012, when compared to sole sugarcane. The combination of herbicide treatments along with the intercultivation of peas resulted in an enhanced weed control in sugarcane. Higher rates of oxyfluorfen (0.234 kg ha^{-1}) and pendimethalin (0.75 kg ha^{-1}) were more effective in controlling weeds than the weedy check. When compared to manual weeding, the presence of weeds in untreated plots led to a reduction in crop yield by 27% to 31% for peas, 29% to 45% for cabbage and 46% to 55% for garlic. Peas, due to its rapid ground cover growth, play a vital role in suppressing weed growth. The efficient use of herbicides not only controls weed effectively but also diminishes their competitive impact on crop yield, resulting in a significant increase in the yield of peas, cabbage and garlic when compared to fields left unchecked for weed growth (Kaur *et al*., 2015).

A study conducted by Kaur *et al*. (2016) in sugarcane-canola intercropping systems in northern India revealed that Indian mustard exhibited better weed suppression compared to both oilseed rape and sole sugarcane. This superior weed control could be attributed to Indian mustard due to its greater production of secondary branches and its planting arrangement, with two rows, in contrast to oilseed rape's single-row arrangement. The application of pre-emergence herbicides, specifically pendimethalin (0.75 kg ha^{-1}) and alachlor (1.875 kg ha^{-1}), effectively managed weeds in these intercropping systems. This herbicide application also resulted in an average increase of 41% in seed yield for oilseed rape and 15% for Indian mustard when compared to the unchecked weedy condition. Furthermore, the use of these pre-emergence herbicides boosted net returns by USD 286 to USD 317 per hectare when compared to the weedy check, indicating their economic benefits in terms of improved crop yields and weed control.

The application of ametryn and trifloxysulfuron ready-mix @ 1097.3 g a.i. ha^{-1} , along with 27.8 a.i. ha^{-1}, at 15 DAP, is recommended for improved weed management in sugarcane when it is intercropped with green gram in Eastern India. This approach can effectively delay the emergence of perennial weeds and potentially help in preventing the development of weed resistance. Additionally, over time, it can reduce the weed seed bank in the region. This ready-mix herbicide solution could be adopted in irrigated sugarcane-growing areas across various states in India to enhance weed control strategies and promote better crop management practices (Banerjee *et al*., 2017).

Among the various pulse intercrops, the sugarcane-cowpea intercropping system exhibited the highest weed smothering efficiency of 36.3%, followed by sunhemp (32.3%) and soybean (32.0%), as compared to growing sugarcane alone, in a study conducted in tropical India. This increased efficiency is attributed to the rapid growth of intercrops, which tend to suppress weed populations more effectively than sole crops. It's worth noting that intercropping maize with legumes also reduced weed density when compared to a pure stand of maize. This reduction is attributed to the decreased availability of light for weed germination and growth, along with the weed-smothering effectiveness of leguminous plants (Geetha *et al*., 2018).

Field studies conducted by Bhullar *et al.* (2006) in spring-planted sugarcane based intercropping systems showed that a single pre-emergence application of pendimethalin @ 0.75 kg ha^{-1} or the pre-plant incorporation of trifluralin @ 1.0 kg ha^{-1} demonstrated effective control of annual weeds. Furthermore, these herbicide treatments resulted in sugarcane yields, intercrop yields and net returns that were comparable to the results achieved with two rounds of hand hoeing. However, it is important to note that these herbicides did not exhibit their herbicidal effects on *Cyperus rotundus*, a particularly troublesome perennial weed. This implies that additional weed control measures may be needed to effectively manage *Cyperus rotundus* in sugarcane fields.

Kumar *et al.* (2017) conducted an experiment with the objective to determine the most effective method for weed control to maximize the productivity of sugarcane-wheat intercropping system. In this study, all the weed control treatments, whether chemical or cultural methods, which included herbicide application and manual hoeing, effectively suppressed weed growth when compared to the unweeded control. Among the herbicidal spray treatments, the application of sulfosulfuron @ 25 and 37.5 g ha^{-1} yielded the lowest overall weed dry matter.

Consequently, these treatments exhibited the highest weed control efficiency, with an average efficiency of 61.2% and 63.5%, respectively, over a span of three years.

Ndarubu *et al.* (2000) reported that under the intercropping systems of sugarcane with soybean and sesame, the growth and biomass production of weeds were notably reduced. A weed control approach that combined a pre-emergence application of diuron @ 2.0 kg a.i. ha^{-1} with a post-emergence application of dimethametryn at a rate of 3.0 kg a.i. ha^{-1} at 12 weeks after planting (WAP) was found to be just as effective in controlling weeds as monthly manual hoe-weedings. Intercropping sugarcane with soybean or sesame while using the diuron and dimethametryn herbicide combination increased the efficient utilization of land, as indicated by farm returns. Specifically, it resulted in a 31% increase in land utilization when sugarcane was intercropped with soybean and an 11% increase when intercropped with sesame. This suggests the potential benefits of this weed control method in improving land productivity and returns for farmers.

CONCLUSION

In the journey to secure a sustainable future for sugarcane farming in India, intercropping has emerged as a potent ally. Our review has underscored the manifold benefits that intercropping can bring to sugarcane cultivation. However, there is a significant gap between the potential of intercropping and its adoption on a larger scale by Indian growers. Intercropping in sugarcane, with its capacity to enhance productivity, improve soil health and reduce pest and disease pressures, offers a win-win solution for farmers. It provides a diversified income stream, offering economic resilience in the face of fluctuating sugar prices and climate uncertainties. Furthermore, it contributes to reduced environmental impact by minimizing the reliance on synthetic inputs and promoting sustainable land use practices.

Yet, despite the compelling advantages, the widespread adoption of intercropping in sugarcane remains a challenge. To harness the full potential of intercropping, there is a need for a concerted effort from agricultural stakeholders, policymakers and farmers. A promising avenue for expansion lies in identifying areas where short-duration crops can be integrated with sugarcane. It is a vision well worth pursuing for the prosperity of both farmers and the nation.

Conflict of interest

All authors declare that they have no conflicts of interest.

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