Discover Agriculture

Review

Prospects of the sugarcane industry in Fiji for carbon sequestration and environmental sustainability amidst changing climate: a critical overview

Shamal Shasang Kumar[1] · Kaashvi Krishna Goundar[2] · Owais Ali Wani[3] · Shazil Sharfaraz Hassan[2] · Shavneel Kumar[4] · Vinit Vinay Kumar[5]

Received: 7 September 2024 / Accepted: 16 October 2024
Published online: 29 October 2024

Abstract
Fiji, a South Pacific island nation relies on its longstanding sugarcane industry for economic growth. However, this industry is threatened by climate change (CC), endangering lives and the economy. Sugarcane production has been declining due to changing climate conditions for over a decade. Despite its small carbon (C) footprint, Fiji is actively engaged in global efforts, including leading COP23, to prevent severe CC scenarios. As part of this, Fiji aims to achieve net-zero greenhouse gas emissions (GHGE's) by 2050 through the Paris Agreement. Scientists worldwide are exploring ways to reduce C emissions and boost soil C absorption. Sugarcane, Fiji's oldest and largest cultivated industry has an opportunity to mitigate CC and improve soil sustainability. This can be achieved with proper land use and management. Advanced techniques like plantstone C, residue retention, conservative soil tillage, crop rotation, sugarcane bagasse biochar, and nutrient management practices can increase C in Fiji's soils. This article provides a comprehensive overview of the current state of knowledge and advancements that can be attained in the sugarcane industry. It covers various aspects, including the impact of CC in Fiji, the history of the sugar industry, changing industry status, market conditions, challenges, enhancement strategies, and the prospective potential for C sequestration and sustainability in the sugarcane sector. A key research priority is to establish optimal management practices that can increase C storage potential, building on a deeper understanding for greater sustainability in sugarcane production.

Keywords Sugarcane Industry · Pacific Islands · C Sequestration · Sustainability · Climate Change

1 Introduction

Variations in climatic conditons such as rainfall intensity, temperature, and natural disturbances (floods, cyclones, and droughts), are permanently coupled with some of the external causes of CC, which include the continuous increase in the level of anthropogenic greenhouse gases (GHGs) [1]. The gradual upsurge in temperature is exacerbated

✉ Shamal Shasang Kumar, shamalkumar1997@gmail.com; Kaashvi Krishna Goundar, kaashvi@srif.org.fj; Owais Ali Wani, owaisaliwani@gmail.com; Shazil Sharfaraz Hassan, shazil@srif.org.fj; Shavneel Kumar, ssavnil66@gmail.com; Vinit Vinay Kumar, vk725885@gmail.com | [1]Crop Research Division, Ministry of Agriculture & Waterways (MOA & W), Rakiraki, Fiji. [2]Department of Crop Improvement, Sugar Research Institute of Fiji (SRIF), Lautoka, Fiji. [3]Division of Soil Science and Agricultural Chemistry, Faculty of Agriculture, Sher-E-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu & Kashmir 193201, India. [4]Department of Forestry, College of Agriculture, Fisheries and Forestry, Fiji National University, Nausori, Fiji. [5]Department of Plant Pathology, College of Agriculture, Fisheries and Forestry, Fiji National University, Nausori, Fiji.

by the burning of fossil fuels, with agriculture contributing 14% of all anthropogenic GHGE's and the transition of native lands to cropland causing another 17% through deforestation [2]. In addition to its effects on CC, agriculture is influenced with estimates of increased threats to regional and global food security [3]. Fiji, a Pacific Island country in Melanesia, part of Oceania, situated in the Southern Pacific Ocean, is highly vulnerable to the changing climatic conditions and their effects on the terrestrial and oceanic ecosystems. Every year, the country is vulnerable to cyclones, droughts, and earthquakes. Convergence zones like the zonal westerlies are affected by a number of variables, such as coupled Hadley cells, trade winds, and Walker circulation regimes. The primary mode of variability from year to year that affects and influences the climate in the Pacific region where Fiji is located are semi-permanent subtropical high-pressure belts and the El Nino Southern Oscillation [4].

Sugarcane (*Saccharum officinarum* L.), a native of South-Southeast Asia, is one of the oldest commercial crops grown in tropical and subtropical areas [5]. Fiji's sugar industry was founded in 1882, and by 1883, sugarcane farming had displaced copra as the country's principal export crop [6]. The cultivation of sugarcane quickly took over as the economic engine of the country. The foundation of the Fijian economy and the development of the country has been sugar since the beginning of the industry more than a century earlier. Sugar has remained the foundation and backbone of the Fijian economy and the development of the country since the industry's establishment [7]. This industry has significantly improved the socioeconomic conditions of the people living in the cane belt, especially in rural areas. It has also facilitated commercial agriculture, created jobs in small and medium-sized businesses, established market retailers, cash crop farming practices, and improved medical advancement, well-being, and credit options [8]. Fiji's agricultural sector is dominated by subsistence farming and sugarcane production [9]. Previously, the sugar sector helped drive Fiji's economy and contributed to its gross domestic product (GDP). Even then, sugarcane yields have been decreasing since the year 2000, with current yields of lower than 2 million metric tonnes per year and less than about 4 million metric tonnes before 2000 [8]. The Fijian sugar industry, which has benefited from numerous agreements and treaties since 1975, is now unviable due to the preferential sugar pricing contracts' expiration in 2017. The decline in sugarcane production is driven by several factors, including reduced acreage from late or unrenewed land leases, rising labor costs, the younger generation shifting to white-collar jobs, and declining interest in the industry. Additional contributors include lower sugar recovery, higher agricultural expenses (fertilizers, transport, and harvesting), and increased labor demands [10]. For high biomass crops like sugarcane, soil quality is crucial as it influences nutrient dynamics, moisture availability, and rooting behavior through its biological and physicochemical properties [11]. The cultivation of sugarcane as a plantation crop, which is widespread in many nations, efficiently reaps the advantages of multi-ratooning (growing numerous ratoon crops following a single planting), which results in soil enrichment as a natural process. Among different strategies used for sequestering C in soil, a sustainable approach is capturing carbon dioxide (CO_2) by extending natural vegetation and sustainable farming practices [12]. Cropland soils act as important C sinks and might significantly impact the lowering of atmospheric C [13]. Long-term sugarcane cultivation produced sugarcane derived-C sequestration that more than made up for losses in native soil organic carbon (SOC) stock [14].

Several studies published globally have demonstrated that practicing conservation tillage enhances soil C sequestration and improves nutrient dynamics [15, 16]. Scientists have learned that a natural mechanism in plants, mainly sugarcane, is crucial in reducing CO_2 emissions and the effects of global warming. This is referred to as plantstone C or phytolith occluded C. For thousands of years, the plantstone C has securely stored 300 million tonnes of CO_2 every year that would otherwise be lost to the surrounding [17]. According to [18], the application of biochar made from sugarcane could raise soil C stocks by 2.35 t C ha^{-1} annually. Retention of sugarcane residue influences soil C sequestration and fertility in a highly site-specific manner [19]. In a study by [20], it was discovered that keeping straw on the soil's surface and using a no-tillage technique when planting sugarcane are both seen to be effective strategies for increasing C sequestration. The no-cane burning or trash farming method can lead to cane production to go from a C emitting to a C sequestering (C negative) process due to direct C sequestration from humus-C incorporated in the soil at 6.0 t CO_2 ha^{-1}, evasion of emissions of CH_4, CO, and N_2O during cane burning at 1.794 t CO_2 ha^{-1} and increased ratoon cycles from the customary one to two ratoons to four up to six ratoons leads to avoided CO_2 emission at 0.257 t CO_2 ha^{-1} per ratoon [21]. This review provides us an in-depth overview of the sugar industry in Fiji, its potential prospects and management strategies that can sequester C and maintain sustainability given the advent of changing climate conditions prevailing in the pacific region.

2 Current climate change scenario: Fijian perspective

Global warming at present and predicted CC for the twenty-first century are the two main shifts that have abruptly occurred over the previous 60 years. Globally, CC is a complicated intergovernmental challenge that impacts a wide range of natural, environmental, sociopolitical, and economical disciplines [22]. CC is no-hoax and is a major problem that all nations have faced since industrial revolutionization (IR), which has caused heightened global average annual temperatures [23]. The earth's climate is in grave problem and is greatly exacerbated with the advent of the IR. Discussions about the earth's temperature increase have been more heated and gained more attention in recent years due to extreme weather. It is not reasonable to determine the precise implications of CC on a specific basis, as evidenced by the rising level of recognition and integration of climatic uncertainty at both local and national levels of policymaking [24]. The comprehensive long-term patterns of rainfall and temperature, along with other elements like air pressure and moisture, are used to quantify the extent of CC. Inconsistent weather patterns, global ice sheet melting, and the ensuing accelerated sea level rise are some of the other most well-known domestic and international effects of CC [25]. Before the IR, the atmosphere's primary producers of GHGs, such as CO_2, CH_4, N_2O, and H_2O, were naturally assumed to be volcanoes, forest fires, and seismic activity [26].

The United Nations Framework Convention on Climate Change (UNFCCC) reached a significant agreement to combat CC and intensify, accelerate, and increase the actions and investments required for a sustainable low-C future at the Conference of the Parties (COP-21) in Paris on December 12, 2015. The Paris Agreement's main goals are to enhance the global response to the threat of CC and keep the rise in average global temperature this century well below 2 °C [27]. The agreement seeks to facilitate the adaptation of nations to the impacts of CC and to align financial flows with low- GHGE's and climate-resilient growth [28]. During this period, CC is thought to be most closely related to anthropogenic activity. The elevated rate of industrial activity leads to GHGE's, which are to be blamed for the temperature increases, mainly in terms of fossil fuel burning [29]. The consequences of CC are determined by the greenhouse effect (GHE) [30]. Apart from the industrial revolution, other anthropogenic activities include deforestation, large-scale fuel-based automation in agriculture, burning of agricultural waste, burning of oil and coal, and national and domestic transportation [31]. The previous study on the global temperature during the past 100 years has shown a substantial rise in temperature above 1 °C [32]. The earth has been experiencing accelerated warming since the mid-1990s [33].

Fiji's contribution to human-induced (anthropogenic) CC is minimal due to the country's small geographical area and the minimal level of development. However, despite such conditions, Fiji will need to participate in international negotiations to stop the worst-case scenarios of CC. Tuvalu is another alarming example of how small nations which do not contribute significantly to the gas emissions equally suffer, which is predicted to be fully submerged within the next few years [34]. Even if international efforts to reduce GHGE's are successful, Fiji, like all other Pacific Island Countries (PICs), will have to adjust to the changes that the climate and ocean system have already undergone as a result of earlier GHGE's [35]. Based on the existing climatic trend in Fiji, [36] deduced that the temperature is expected to increase by ~ 0.9 and ~ 1.5 °C by 2050 and 2100, respectively. This projected effect demonstrates how CC impacts many areas, including food and water security, reef and fisheries productivity, and many more in Fiji. The livelihoods of the Fijian population and the island's marine and terrestrial ecosystems are threatened by changing weather conditions. Fiji's sea level is rising by 6 mm yearly, which is faster than the global average (1.4 mm), posing a major threat to the whole country [37]. Coastal flooding affects cattle and crops, reducing the country's supply of necessities and forcing populations to migrate at a pricey expense. The country's GDP and overall economy owe 13.82% to the agricultural sector as of 2021 [38]. In terms of its ability to produce, it is also the most susceptible to climatic changes. The El Nino drought that struck Fiji in 1997–1998 served as a historical example of the devastating consequences that CC may have on the agricultural sector, notably on the subsistence farming and sugar business in the Western Division. Specifically in the sugarcane sector, it caused a revenue loss of F$104 million. In the most severely damaged places, such as Viti Levu Western region, Vanua Levu, and the Yasawas, about 90% of the population received food and water supplies [35]. One of the strongest cyclones ever recorded for the Southern Hemisphere, Tropical Cyclone (TC) Winston, struck the country in 2016 and caused immense destruction, leaving the majority of people with nothing more than the clothing on their backs. According to estimates, TC Winston caused F$1.99 billion worth of damage, including F$76.6 million in damages to education and F$542.0 million in losses to the agricultural sector [39]. The forestry sector suffered a loss of F$29.3 million (5%), livestock F$14.3 million (3%), sugarcane F$75.3 million (14%), crop F$216.4 million (40%) and the fisheries sector a loss of F$206.5, accounting 38% of total losses (Fig. 1) [40]. The agricultural sector, which includes the subsectors of crops, animals, and fisheries, is represented in Fig. 2 by the fluctuation in production losses brought on by TC Winston.

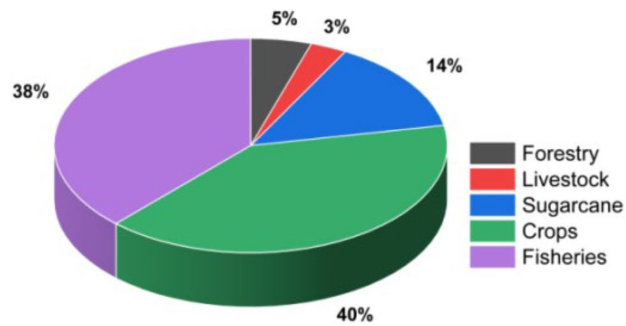

Fig. 1 Tropical cyclone Winston related percent damage in agriculture subsectors. Source [40]

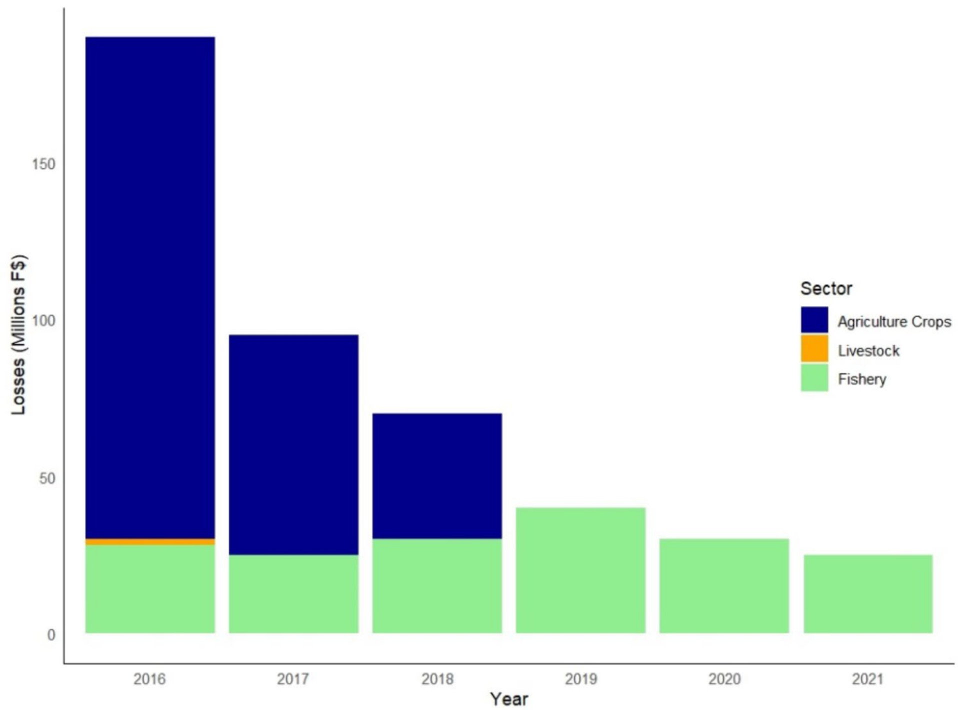

Fig. 2 Anticipated losses of productivity in the agriculture sector over time. Source [40]

According to estimates, Fiji's total GHGE's (CO_2 equivalent) as of 2018 were 2,820 kt CO_2, up from 1,820 in 1990 over the previous 28 years [41]. As of 2020, Fiji has produced 1.39 million tonnes of CO_2 emissions from fossil fuels and industry [42]. Fiji is extremely vulnerable to cyclones and floods due to its low-lying atolls. So, for Fiji, the damage brought on by CC is nothing new. Sea flooding frequently occurs as a result of tropical cyclones passing close to the coast. Low-lying coastal areas have also been inundated by large seas brought on by distant deep depressions and severe high-pressure systems. Fiji's civilization and economy are under peril due to CC. CC worsens weather patterns, increases disease rates as global temperatures rise, intensifies destructive storms as oceans warm, and disrupts agriculture as saltwater incursion damages existing crops. On Viti Levu, the largest island in Fiji, these environmental changes are predicted to cause economic losses of up to F$52 million yearly, or approximately 4% of the nation's GDP [43]. The International CC Commission predicts that if current trends in fossil fuel use and deforestation are not reversed, the average global temperature would climb by 6° C in the following century [44]. As COP23's president nation, Fiji pushed for the implementation of the Paris Agreement in order to achieve net-zero global GHGE's by 2050, as the first country to ratify the Paris Agreement on CC [45].

Atmospheric CO_2 is the most intrinsic GHG in the world. The global atmospheric CO_2 concentration as of 2022 is 418.43 ppm compared to 315 ppm in 1958 [46]. Currently the CO_2 concentration is 5.04 ppm greater than in the year 2020 (413.39 ppm) and 32.80% greater than in 1958. In the end-of-century, it is projected that the atmospheric CO_2 levels could reach 900 ppm if global temperatures continue to rise and fossil fuel reserves are primarily depleted. Fossil fuel emissions between 1850 and 2018 were 440 ± 20 pg C (1 pg C = 1015 g C) as CO_2 [47]. The Emission Database for Global Atmospheric Research (EDGAR) reports that Fiji's 2016 fossil CO_2 emissions were 1,703,193 tons. The proportion of C emissions increased by 7.28% from the previous year, or by 115,545 tons over 2015, when there were 1,587,648 tons of

CO_2 emissions. Based on an estimated 2016 population of 872,399, Fiji's CO_2 emissions per capita are 1.95 tons, up 0.12 from the 1.83 tons per person recorded in 2015. Such change in CO_2 emissions per capita represents a 6.5% shift. Fiji's CO_2 emission and cumulative CO_2 emission for the year 2020 were 1,393,413 and 49,428,747.00 tons, respectively (Fig. 3a, b) [48]. Fossil fuel combustion for electricity production and industrial manufacture of materials like cement accounts for most CO_2 emissions. Fiji has emitted 54,571 tons of CO_2 through the manufacturing of cement and 1.34 million tons of oil as of 2020 (Fig. 4). In 2019, Fiji's GHGE's, measured in tonnes of CO_2 equivalents, were as follows: 810,000 tonnes from transportation, 520,000 tonnes from agriculture, 350,000 tonnes from aviation and shipping, 340,000 tonnes from electricity and heat, 300,000 tonnes from manufacturing and construction, 150,000 tonnes from industry, 130,000 tonnes from waste, 120,000 tonnes from under buildings, and 10,000 tonnes from other fuel combustion mechanisms (Fig. 5).

3 Background history of sugarcane industry in Fiji

Sugarcane is thought to have originated in the South Pacific islands and Papua New Guinea, it's also plausible that the early Melanesians who migrated brought it with them [49]. Sugarcane was identified growing in Fiji when the first explorers and settlers from Europe came upon it. It is known that Fijians produced sugarcane primarily for chewing, and that they utilized the juice to sweeten food [50]. On the small island of Wakaya, David Whippy produced the first sugar in Fiji for commercial usage in 1862. Still, it did not become economically significant until the 1870s, when Colonial Sugar Refining Enterprise Limited (CSR), an Australian company, arrived. As the main export of the country, sugar had taken the place of copra, a position it still occupies today. Ratu Cakobau gave the sugar industry an early boost by awarding 500 pounds sterling to those workers who would be the first and best cane grower, yielding 20 tons of sugar produced from locally cultivated cane. Ratu Cakobau was worried about the deterioration in Fiji's economy in 1871 due to internal unrest and cotton's failure [51]. Since 1874, sugarcane has been the primary agricultural crop in Fiji, playing a vital socioeconomic and cultural role. The British government struggled in the early days of colonial rule to motivate locals and residents of neighboring Pacific Island nations to work on sugarcane plantations. In order to protect the traditional way of life, the British avoided using Fijians as extensive wage labor [52]. Indentured Indian laborers were brought by the British government to work on plantations for cotton, coffee, sugar, and other commodities in 1879. Many Indians remained in Fiji as sugar replaced other crops as the main cash crop until the indenture system was abolished in 1916. Later, the indigenous Fijian (iTaukei) community was included in the expansion of sugarcane growing. In 1999, the

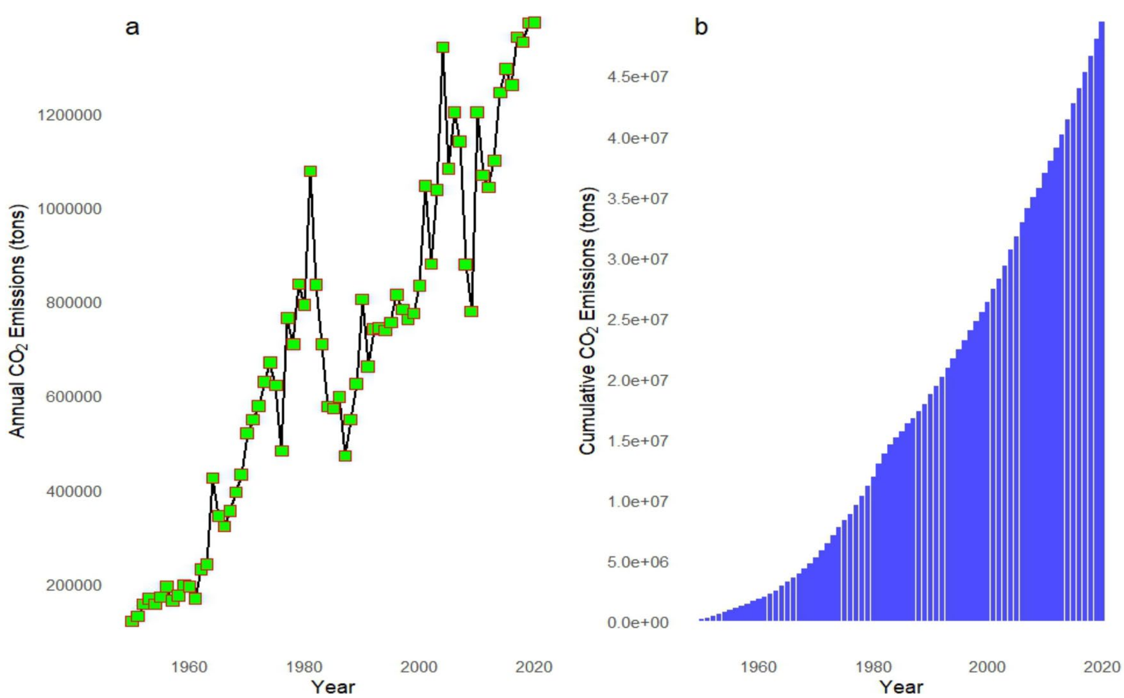

Fig. 3 Annual (**a**) and cumulative (**b**), CO_2 emissions, Fiji. Source [48]

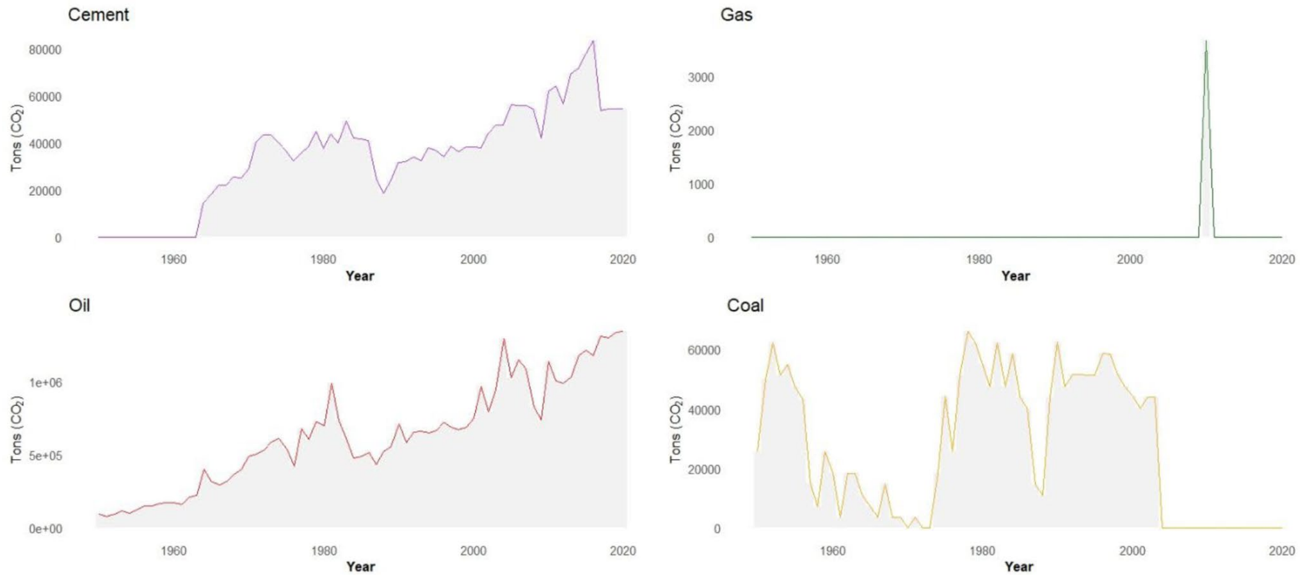

Fig. 4 CO_2 emissions by fuel type, Fiji. Source [48]

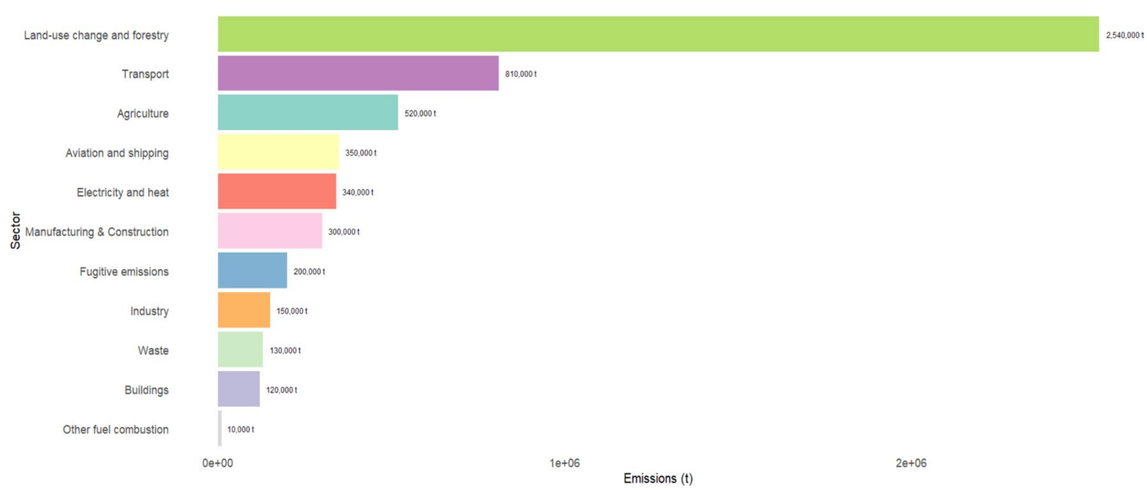

Fig. 5 Greenhouse gas emissions by sector, Fiji. Source [48]

majority (70%) of sugarcane growers in Fiji were Fijians of Indian descent, with about 30% being iTaukei [8]. In total, 34 small sugar mills were constructed around the nation of Fiji in the 1870s. It was believed that the wet regions of Fiji near Suva would produce higher yields, so all of the early sugar developments with the exception of Nadroga took place there. Cane yield was present, but sugar content was rather low. As a result, none of the wet zone mills were operational [53]. Compared to Indians, iTaukei farmers are declining at a faster rate. The quick decline in the number of iTaukei farmers can be attributed to a wide range of issues, including a lack of technical expertise and support, a lack of desire, and the conviction that the rewards from sugarcane farming are not worth the effort [54]. The sugarcane yield in 1999 was 3.96 million tonnes under 64,535 hectares. But as of 2019, just 37,105 hectares of sugarcane totaling 1.70 million tonnes were crushed [55]. The country's sugar industry is among the three main sources of foreign exchange earners [56]. For more than a century, the Fijian economy's expansion has been regulated by the sugar industry; nevertheless, sugarcane production has been declining for the last 15 years [8]. There are still a significant number of Indian farmers who grow sugarcane, despite the fact that their numbers are declining. Fiji's sugarcane industry has a major impact on the nation's economy, generating 1.7% of the GDP and about 8% of all exports in the form of sugar and molasses [57]. The majority of sugarcane is cultivated in Fiji are from Viti Levu, the largest island, and Vanua Levu, the second-largest island, respectively.

There are three sugar mills in Viti Levu, located in Lautoka, Ba, and Rakiraki (although the Rakiraki mill is not currently in operation). While, Labasa is the only sugar mill on Vanua Levu (Fig. 6).

4 Pre- and post-status of the sugar industry and sustainability of cane production in Fiji

The sugar industry in Fiji was the single largest industry during the 1970s, but towards the middle of the 1980s, its importance began to diminish in relation to other sectors and the growth of the economy [58]. In recent years, the industry has faced significant challenges that threaten its long-term sustainability. One of the primary factors contributing to the decline of the sugar industry in Fiji is the non-renewal of land leases. As landowners chose not to renew leases, the available land for sugarcane cultivation has diminished, leading to a drop in production. This issue is compounded by the expiration of preferential trade agreements with the European Union (EU), which previously allowed Fijian sugar to be sold at higher prices. The withdrawal of these preferential prices has reduced profitability for farmers and increased vulnerability to global market fluctuations [59]. Farmers, faced with these challenges, are increasingly diversifying into non-sugarcane crops or seeking employment in other sectors. High production costs, labor shortages, and the younger generation's decreasing interest in farming have further contributed to the sector's struggles. Moreover, the impacts of CC- rising temperatures, shifting rainfall patterns, and more frequent cyclones—pose additional threats to sugarcane yields and soil health [60]. The COVID-19 pandemic has also exacerbated the industry's woes, disrupting global supply chains and reducing demand for Fiji's exports. However, some efforts are being made to address these issues.

The CSR's decision to depart from Fiji in 1973, after over 100 years of engagement in the sector, was one of the most significant moves in the industry's history. The decision was made due to a dispute over the conditions of a new sugarcane deal. The sugarcane contract, in force since 1960, was due to end in 1970. Arbitration was requested after failed negotiations on the parameters of a new contract [53]. The decision by Lord Denning to implement a shared formula, whereby

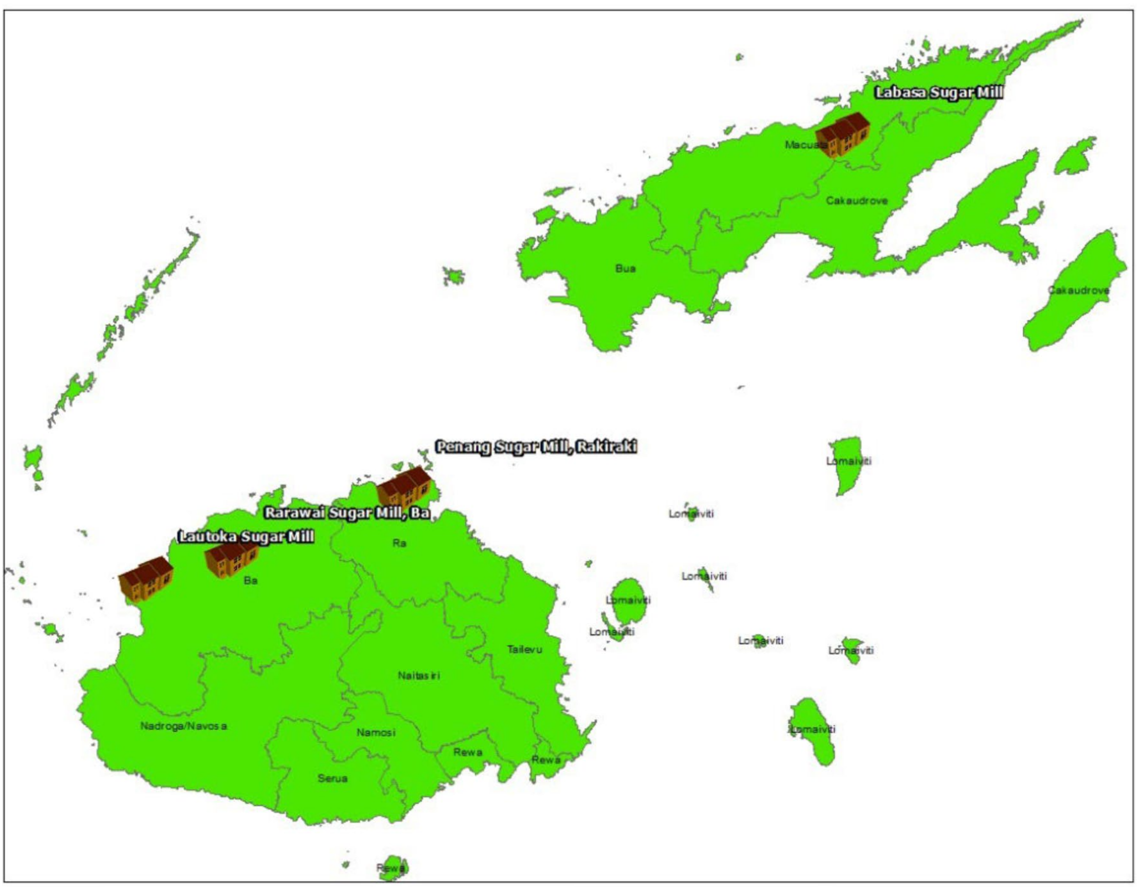

Fig. 6 Sugarcane mills in Fiji. Source [Created by author]

growers would receive 65 percent of the proceeds from the sale of sugar and molasses with a minimum price of F$7.75 per tonne and the miller would earn 35 percent or less, caused a stir among millers (CSR). They were adamant that the Lord Denning-awarded sharing formula would not result in viable operations, and that CSR in Fiji would be discontinued as a result [53]. The Fiji Sugar Corporation Limited (FSC), a publicly traded corporation set up by the government to take over sugar milling, took over operations on the first day of April 1973, ending CSR's operations in Fiji. With 68 percent of the shares, the government holds the bulk of the Corporation's stock. People and organizations in Fiji own the remaining shares. The organization of the sugar business remained unchanged for many years after the FSC took over CSR's milling activities. When the FSC took over milling operations, one of its main concerns was the output trend that was dropping. From 2.46 million tonnes in 1973 to 2.08 million tonnes in 1974, cane production fell, and it stayed there in the early years of the FSC. The Denning Award did not prompt CSR to prioritize boosting output. Concern and dread about the future of the sugar sector also followed the revelation of the CSR's decision to leave Fiji. It was clear that farming procedures had generally been neglected, and that fertilizer had not been applied properly or on schedule. Lower crop productivity is just one of the many problems. Sugar yields will be lower if crop production is lower. For instance, the sector produced 437,921 tonnes of sugar in 1996. However, by 1998 the industry was only able to produce 364,000 tonnes of raw sugar, earning the nation US$122.9 million and accounting for 30% of Fiji's agricultural GDP. As a result, the sugar output fell by approximately 100,000 tonnes [61].

Numerous macro- and micro-issues have been plaguing the sugar sector. The following are on the decline: sugarcane production, the number of farmers, farmer confidence, the loss of productive land to urbanization, ineffective milling, the environment, CC, and pests and diseases [62]. The EU and the ACP (African, Caribbean, and Pacific Islands) governments' 2003 Cotonou Agreement was made feasible by the Convention's expiration in 2000 [63]. The advantageous sugar price was only maintained through 2012. Later, despite warnings not to, this was explicitly stated that there would be no additional extensions and was prolonged for a further five years until 2017 [64]. According to the most recent sugarcane reports, the state's inability to resolve the land lease issues has resulted in a 60% decrease in cane production over the years from what it was in the 1990s; farmers are leaving the industry and moving forward with agricultural commodities, leaving our young generation to carry on the legacy and pave the way for only white collar jobs. With an area of 35,670 hectares under sugarcane production, a total of 1.83 million tonnes of sugarcane were processed from 38,427 hectares in 2015 as opposed to 1.4 million tonnes in 2021 [8]. There were 18,000 farmers in the industry in 2001, but there are currently just 11,400 growers, which is a severe reduction. The average cane yield decreased from 56 t/ha in 1996 to 47.56 t/ha in 2008, 57.72 t/ha in 2006, and 47.81 t/ha in 2005 [65], and it continued to decline until it was 42.1 t/ha in 2021. This decline was directly caused by the production of sugar. The Sugar Industry is battling social and environmental constraints that have drastically affected the sugar industry in recent years, with prolonged drought, flooded waters, and cyclones damaging the sugarcane fields. Due to seawater intrusion, more than 500 ha of land has become saline and unfit for sugarcane cultivation in Vanua Levu [66]. The year 2019 experienced the rage of TC Sarai, which led to a decline in the crop harvest to 1,806,572 tonnes, against a pre-crush estimate of 1,850,650 tonnes. Unexpected weather patterns also led to a drop-in sugar cane quality impacting the total sugar produced for the year.

To address production issues and secure a more sustainable future, a range of sustainable practices is being promoted across the sugarcane sector. One of the key strategies for ensuring the sustainability of sugarcane production in Fiji is the promotion of integrated soil fertility management. Farmers are being encouraged to adopt organic fertilization methods, such as using compost and green manure, to reduce dependency on synthetic fertilizers that contribute to soil degradation and environmental pollution [67]. Organic farming practices not only enhance soil health but also improve water retention and reduce nutrient runoff, which is critical for maintaining the ecological balance in sugarcane-growing areas. Water management is another crucial aspect of sustainable sugarcane farming. With the increasingly erratic rainfall patterns associated with CC, techniques such as optimizing water schedules with trash mulching are being promoted to optimize water use efficiency and prevent soil erosion. These practices are designed to improve water efficiency and ensure that crops receive adequate moisture, even during dry spells [68]. In regions prone to drought, farmers are also encouraged to adopt drought-resistant sugarcane varieties that can thrive in less favorable conditions, minimizing the risk of crop failure. Efforts are also being made to reduce the C footprint of sugarcane farming. The use of sugarcane by-products- such as bagasse, a fibrous residue from sugarcane processing- for bioenergy production is gaining momentum. Bagasse can be used as a biofuel for electricity generation, contributing to Fiji's renewable energy goals and reducing reliance on fossil fuels [69]. This approach not only adds value to the sugarcane crop but also aligns with global sustainability efforts to mitigate CC.

Another promising avenue is the adoption of precision agriculture technologies. Through the use of drones, satellite imagery, and soil sensors, farmers can monitor soil health, moisture levels, and crop growth in real-time, allowing them to make more informed decisions on fertilizer application, irrigation, and pest control. This reduces resource waste, minimizes environmental impact, and increases the overall efficiency of farming operations [70]. Additionally, the sugar industry is working with local communities to promote agroforestry systems, where sugarcane is cultivated alongside other crops and native trees. This practice helps restore biodiversity, reduce soil erosion, and improve land use efficiency, while also providing farmers with additional sources of income from diversified crops [71]. Sustainable practices in sugarcane farming must also take into account the socio-economic conditions of Fiji's rural population. Strengthening farmer cooperatives and improving access to financial resources, such as loans and subsidies, can help smallholder farmers transition to more sustainable methods without compromising their livelihoods. Additionally, training and extension services are essential to equip farmers with the knowledge and skills required to implement sustainable farming techniques.

5 Problematic factors affecting Fiji's sugar industry

5.1 Changing climate conditions and incidence of pests and diseases

Fiji is prone to natural disasters all the time. Since many years, the increased frequency of hurricanes, storms, and flooding has had a severe effect on the sugar industry. In addition, the country has had four to six catastrophic cyclones since 2010, as well as two years of ongoing droughts [72]. Figure 7 demonstrates the major factors influencing sugarcane yield and their interactions. Sugarcane needs enough moisture and the right amount of sunshine for optimum growth. The growth of the crop has been impacted by a considerable variations in weather patterns. Another component of CC has long started to intrude upon sugarcane fields due to broken floodgates and rising sea levels. Similar damage is being done to the sugarcane train lines by the ocean that keeps washing ashore. Therefore, rerouting and remounting these corroding rail lines will require significant financial investment from the sector. Fiji has seen numerous cyclones that have seriously harmed farms, sugarcane fields, and infrastructure supporting the sugar industry. The farmers, who already make a pitiful living from the sugarcane they harvest, are severely harmed by the cyclones. Due to the regular natural disasters, many farmers in Fiji have also lost their houses, farms, and personal belongings. For instance, the sugar sector was severely harmed by the destructive Category 5 Cyclone Winston in 2016 [73]. With winds reaching 330 km/h,

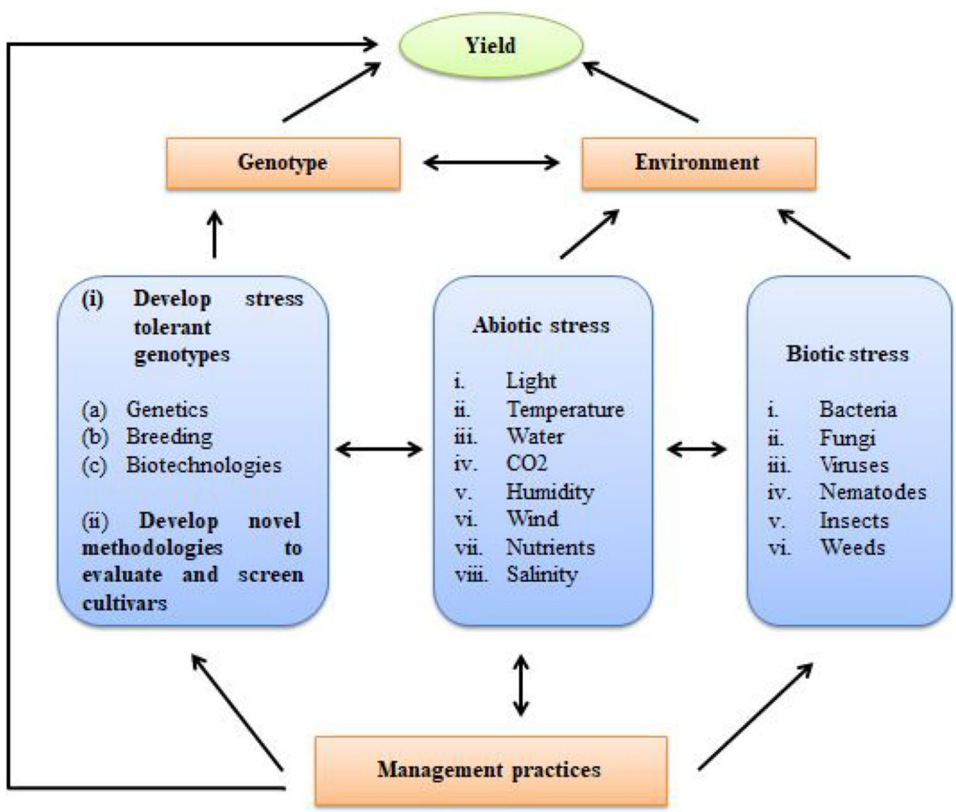

Fig. 7 Flow chart demonstrating major factors influencing sugarcane yield and interactions. Source [Created by author]

it had flattened the farms and uprooted the sugarcane crops. Additionally, several of the farms spent several days under water. The infrastructure and crops of sugarcane were first damaged by Winston to the tune of F$83 million. Additionally, the Tavua-Rakiraki sugarcane-producing districts on the island of Viti Levu suffered the worst losses, accounting for 80% of all sugarcane crops. Following the cyclone, the Penang Mill in Rakiraki stopped operating, and the FSC ruled it non-operational [74]. Farmers, their crops, and their livestock are all significantly impacted by drought. In times of drought, farmers frequently find themselves fighting an uphill battle to sustain their cattle and crops. For a number of reasons, farmers keep animals like bullocks and horses which is utilized for food production and animal traction during the development of various crops, including sugarcane. Due to the scarcity of lush pastures during the dry seasons, farmers are forced to spend money on alternative food supplies like copra and mill-mix to feed their livestock. During dry seasons, some farmers also experience cattle invasions where livestock enter the land to graze on sugarcane and other important crops. The new plants are frequently uprooted as a result of this. Furthermore, recovering them once the crop has been consumed is challenging. The invasion of animals causes farmers to experience significant agricultural losses. If the sugarcane fields are not properly managed, pest and disease infestation is expected. The sugarcane weevil borer (*Rhabdoscelus obscurus*), grasses, shrubs and creepers, rats, mongooses, feral pigs, unattended cattle, ants, and termites are among the common pests in the sugarcane fields. Up to 25% less sugarcane is produced due to weeds. Illas like Fiji Leaf Gall Disease (FLGD) and Ratoon Stunting Diseases can also infect sugarcane crops (RSD). It has been discovered that both illnesses have a devastating impact on rats and newly planted crops [62]. In sensitive cane types, like the Mana variety, the FLGD causes a yield reduction of ~ 100%, whereas the incidence rate of the RSD is estimated to be 28%. The FLGD causes elevated, pale yellow swelling (galls) on the undersidide of the leaf blade and midrib, as well as symptoms that look like the leaf tops, have been "bitten off," which stunts sugarcane plants. RSD is to blame for the plant's slow germination, health issues, and decreased number of stalks, which results in the crop having short, thinner, and stunted leaf growth. The nodes of the mature sugarcanes typically have discoloration in their vascular bundles when they have RSD. The SRIF advises Fiji to prepare for smut disease even if it is not yet common in the nation. The 1970s and 1980s saw an international spread of the smut illness. It is to blame for a 30–100% decline in sugarcane crop productivity. The illness has spread to Australia over the last ten years. Only two countries that produce sugar, Papua New Guinea and Fiji, are free of the smut illness.

5.2 Trade-related issues (Market access loss, faretrade-premium expiration, changing global marker prices and geographic seclusion)

The trade-related problems for the country's sugar sector included loss of market access, the elimination of the FairTrade (FT) premium, fluctuating market prices, and Fiji's geographical isolation from the rest of the world, particularly from significant international sugar markets like the UK and the EU. After the EU ended preferential access for ACP countries in 2012, Fiji was granted a transition period that lasted until September 2017 [75]. Afterwards, the EU began to accept all ACP items on its markets and assured pricing was turfed off, with ACP producers being treated the same as European ones. With this change by the EU, the markets in the EU were open to all ACP members. The EU, however, had also avoided causing market instability with exports from the ACP nations. If the EU and UK markets closes, Fiji will face numerous issues. This will have a stimulating effect and have a domino effect on the country and its people since Fiji produces some of the least sugarcane in the world, but a sizable section of the population depends on the sugar industry to survive. One day, there will be a need to increase the cost of sugar for local markets. Numerous organizational, structural, and systemic issues must be resolved. In the end, a decision made by the EU in this regard will have a significant impact on the price of sugar on the global market and the Fijian sector, particularly the sugarcane growers [76]. This added to the already significant pressure on that industry, prompting FSC to borrow money in order to keep the F$80 per tonne price to farmers, which has become increasingly difficult to do over time. The FSC has been making losses for years for a variety of reasons. Farmers need to be made aware that product quality, not sugarcane production, determines price variations. Consumers want premium sugar in order to compete with other countries. Additionally, the payment to our farmers is a significant issue. Because they don't have the luxury of getting paid three times the market price of sugar, The FT is going. For this there is a need to keep reiterating and emphasizing the need of high-quality sugarcane farming and output.

Since 2010, Fiji has benefited from premium pricing for its sugar due to FT certification, initially implemented by sugarcane producers on Vanua Levu. FT was established as an alternative to conventional trading, fostering collaboration between suppliers and consumers. Its goal was to empower farmers and workers in Fiji by improving trade terms to enhance their working and living conditions. According to a 2012 report from the Secretariat of the Pacific Community

(SPC), farmers certified under the FT program experienced significant financial gains [77]. Taking into consideration all costs and advantages, the analysis predicts that all farmers in Vanua Levu who supply the Labasa sugar mill will see an economic gain of F$9,094,473 over a 12-year period [78]. The FT system motivated farmers to increase their crop production rates by fostering a win–win situation for farmers, millers, and FT organizations in fulfilling their mandates. The subsequent expansion of FT certification to more sugarcane-producing regions in western Viti Levu brought several million dollars in additional financial benefits to growers, offering them significant rewards over the long term. However, in 2015, the Financial Times announced that starting in 2016, they would only accept premiums from sugar sales, which led to immediate financial repercussions for Tate & Lyle Company in the UK, resulting in a loss of F$13 million in revenue [75]. It is quite regretful that the FT has dissolved. Farmers would no longer be able to take advantage of some of the incentives that were previously offered. The verdict of FT will have an impact on crop production, especially for small-scale farmers. Future local development plans will face challenges in the sugarcane fields as well. Whether the FT will ever be replaced is unknown. After the FT premiums ceased to be paid, cane farming communities encountered severe challenges that hampered their efforts to build their societies in a way that benefited families in the sugarcane districts. The F$25 million premia that was paid over the preceding four years, beginning in 2011, from the sales of sugar products registered under FT has assisted producers by cutting their costs through incentives on growing equipment, improving drainage systems, and purchasing fertilizer. The FSC was compelled to hunt for alternative markets to sell the FT-certified sugars as a result of Tate & Lyle's decision to cancel their commitments to buy 100,000 tonnes of sugar at FT premium. Since the end of preferential EU quota access and FT premiums, Fiji has become much more dependent on the annual swings in sugar prices on the world market. Despite the fact that these annual adjustments are a major source of worry for the sugar industry in general and the FSC in particular, the price paid for sugar that exceeds quota normally reflects the price on the worldwide market. Between 2011 and 2015, when the price given to farmers started to fall, Fiji made every attempt to match the price of sugar in other countries. The lower sugar prices hurt local farmers, escalating the simmering tensions between the FSC and the farmers that were already there. The government as a result provided the farmers additional payments on top of the FSC payments. It therefore only had a minor effect, even though it momentarily restored farmer trust.

Fiji suffers from oppression at a distance, just like other developing island nations in the Pacific. The nation's remote location and the small domestic markets are the main impediments to Fiji's economic growth and prosperity. Furthermore, Fiji is cut off from the rest of the world by a great ocean, and high shipping costs tend to impede trade in both domestic and international markets (Fig. 8). Fiji is the sole sugar-producing nation in the South Pacific, and it faces severe challenges for its sugar industry and farmers. Fluctuations in global energy markets worsen these issues. As oil prices rise,

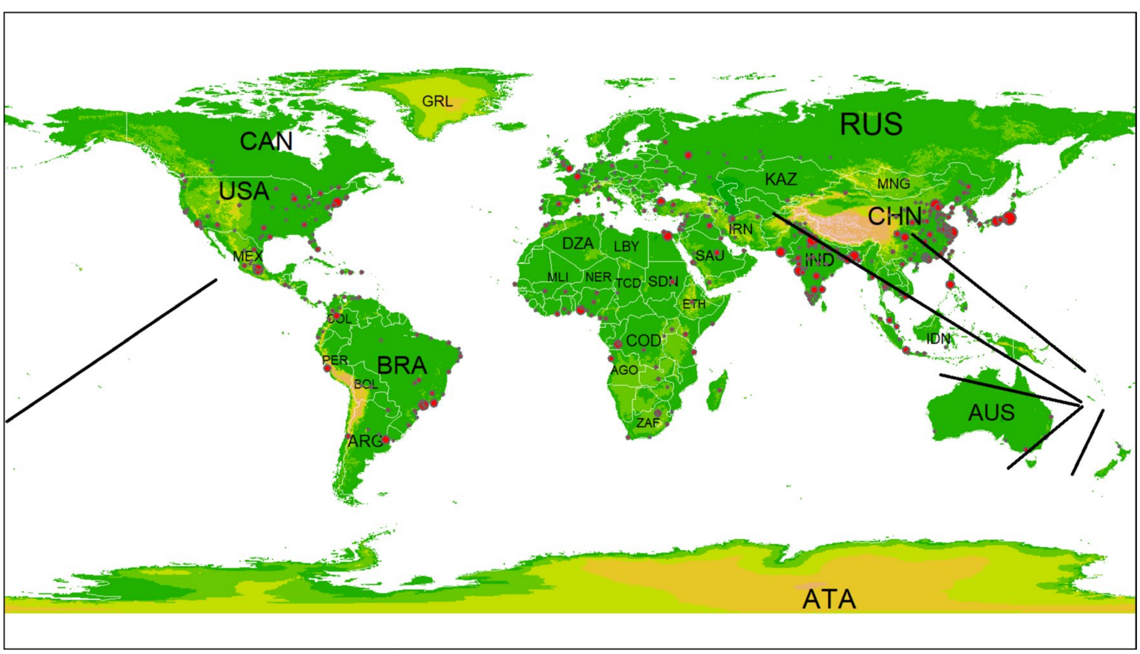

Fig. 8 Map depicting Fiji's separation from the world's largest sugar markets. Source [Created by author]

the cost of fuel for farm machinery, such as tractors, and generators for electricity in rural sugarcane-producing areas without utility access continually increases.

5.3 Issues with the Fijian sugar industry on a macro- and micro level (Decreasing production, falling farmer demographic, urbanization-related loss of productive land and milling inefficiencies)

The macro and micro problems facing the sugar industry have worsened. Alongside a decline in sugarcane production and fewer farmers, valuable land is being lost to urban sprawl, milling efficiency is continuously declining, climate change is impacting yields, and pests and diseases are on the rise. Over the past 20 years, Fiji's sugarcane production has significantly decreased (Fig. 9a and b). It has declined by more than half from 4.06 million metric tonnes of sugarcane crushed in 1994 to 1.83 million metric tonnes in 2014 [79], then to 1.6 million metric tonnes in 2018. In a similar line, the number of registered farmers has decreased. As an illustration, 22,807 farmers were officially registered in 1994. There were only 16,666 of them as of 2018, and only 11,902 of them were still active farmers [55]. From 74,388 hectares in 1994 to 38,248 hectares in 2013, the overall area used for sugarcane production has decreased by almost half [51]. Thus, the area under cultivation had increased before 1990 but began to decline dramatically after that year. The number of

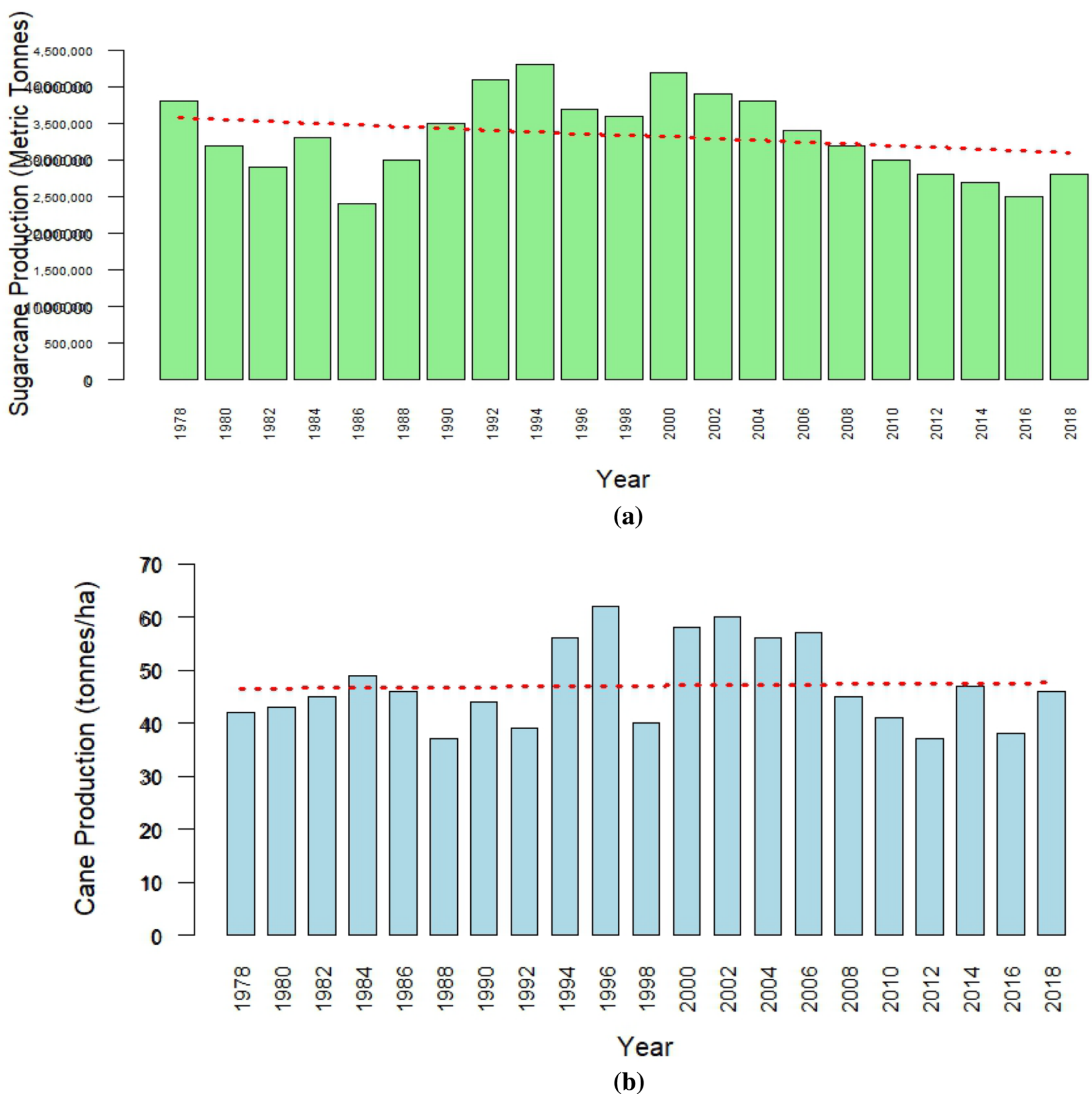

Fig. 9 **a** Sugarcane production (four decades) trends in Fiji. Source [79]. **b** Sugarcane output (tonnes/ha) productivity trend in Fiji. Source [79]

Girmitiya sugarcane growers declined after 1997 as iTaukei landowners failed to renew farm leases. With no support for lease renewals, many farmers lost faith in the sugar industry and left the fields, hastening its decline.

Agriculture, especially sugarcane farming, is seen as unappealing and unprofitable by most in Fiji, particularly younger generations. Many farmers have turned to sugarcane farming as a hobby, driven by sentimental ties rather than serious business. These "hobby farmers" often rely on other income sources, such as businesses or remittances from children abroad, and are not focused on boosting production. This shift threatens the already declining sugar industry, with 80% of farmers now treating it as a side activity rather than a primary livelihood. During the colonial era, most sugarcane districts in Fiji were near mills and railroads. Over the past two decades, urban expansion has claimed much of the prime flat land, which is better for farming than marginal areas like hills or marshes. This has reduced sugarcane cultivation by 20–25 thousand hectares, with only 27% of flat land now used for farming. The remaining sugarcane is grown in less productive, marginal areas.The expansion of inland agriculture has also resulted in a significant increase in the distance between farms and mills. Transport and carting have become significant problems as a result of FSC's poor management of the railway system for carrying the harvests, increasing cartage costs for the farmers.

The FSC has also struggled over time to consistently produce more sugar than the preferred ration due to the frequent faults that happened anytime mill throughput was increased. Furthermore, whether on purpose or not, mill breakdowns have led to scathing criticism from farmers for FSC's poor administrative skills. Similar to this, deteriorating rail networks and mills' inability to handle increasing sugarcane loads have led to longer crushing seasons [80]. Outdated rail systems have significantly delayed the transportation of sugarcane from harvest to mill, leading to a host of operational challenges. Issues such as a broken generator at the mill have halted crushing altogether, and periodic breakdowns of the crushing equipment require time-consuming maintenance. These delays can impair the quality of the harvested sugarcane, as crops remain stored at farms and mills for extended periods. Additionally, a lack of adequate toilets and sanitary facilities at the mills further exacerbates the situation. During the crushing seasons, truckers face daily wait times of up to 15 to 20 h before they can unload their harvested crops and return. This prolonged waiting not only results in lost productive work time for employers but also poses health risks for drivers, who endure uncomfortable and unsanitary conditions during these extended periods.

5.4 Farmer Issues (land tenure security, sugarcane payment, labor scarcity and increasing cost)

Certain issues affecting sugarcane growers in Fiji, such as tenure security, payment delays, labor shortages, and rising costs, are specific to them and not categorized as macro- or micro-problems of the sugar sector in this study. A key concern is the stability of the land tenure system. Under the Agricultural Landlord Tenants Act (ALTA) of 1976, leases are limited to 30 years, and renewal depends solely on the landlord's decision, creating uncertainty for farmers seeking extensions. For the few sugarcane growers who have legal land titles, the issue of land tenure is insignificant. The end of land leases has resulted in a major loss of human resources (household labor) on the farms. Additionally, the expulsion of people from farms has resulted in a loss of labor for agricultural cultivation, harvesting, and transportation-the majority of which the farmer and his family would carry out alone [81]. The resolution of the land tenure system, which has been in place since 1909 when the British colonial authority frozen land ownership titles to protect indigenous property owners, is a key element in the company's commercial future, according to [82].

The sugarcane payment formula in the Master Award, which governs how the FSC distributes profits to farmers, favors increased sugarcane production without considering environmental factors that impact yields. According to Clause 20.2 of the Master Award, the method for calculating the farmer's share of selling revenues is outlined in the Award itself (Table 1). Furthermore, the absence of consequences in the system, particularly for crop production above the "basic farm allotment," had encouraged production above the actual allotments even when the price of sugar remained low. As a result, some farmers have benefited from the "farm allotment" part, while others have found it ineffective. Similarly,

Table 1 Percentage proceeds of the sale of sugar (The Fiji Sugar Industry-Sustainability Challenges and the Way Forward)

Total sugar produced	Grower's share (%)	The corporation's share
Up to 325,000 tonnes	70.0	30.0
For every tonne over 325,000 tonnes up to 350,000 tonnes	72.5	27.5
For every tonne over 350,000 tonnes	75.5	25.0
These percentages are based on the net proceeds of sale		

the preferential quota income created a shared fund accessible to all farmers based on their productivity. This system favored farmers who produced more than their quota without penalties, leading to confusion and poor implementation of the agricultural allotment system. Additionally, the Master Award's payment procedures and methods have been detrimental, primarily for smallholders. For instance, one harvesting season's payment is divided into 3–5 instalments and dispersed in percentages from the sales revenue throughout two subsequent sugarcane seasons.

A major concern for farmers is the labor shortage during harvests. Many farmers' children no longer have the same interest in farming as in the past, and those who do are often viewed as lower class. In earlier times, children working on farms ensured a steady labor supply. Another issue is aging: when an elder farmer passes away, their children often abandon the farm, leaving it idle or selling it. Farmers now rely on outside labor, mainly from nearby villages or distant islands, often iTaukei workers, who are perceived as less dedicated and untrained, resulting in delays. Over the past ten years, there has been a marked growth in demand for sugarcane cutters. For instance, they now want compensation in addition to their normal pay as well as additional amenities like housing and food stipends for live-in employees, tea or juice to drink while working in the field, three meals per day, and reimbursement for travel expenditures. Another labor recruiting requirement that might be incorporated is making lump sum payments five to seven months before to the harvest season to bind the already tiny pool of laborers and prohibit other farmers from extracting them and utilizing them on their crops. Though the laborers, for instance, ask for an advance payment of F$500 per person and the farmer needs three workers to help with the harvest, even if it can later be deducted from their compensation. The farmer must then contend with the challenge of receiving timely and reliable payment from FSC for his harvested produce in order to pay the laborers on time.

The cost of sugarcane production in Fiji remains high despite efforts like planting high-value varieties and government subsidies. Harvesting and transportation alone account for about 50% of total production costs, while other expenses include premium seeds, weedicides, insecticides, and fertilizers. The aging rail systems managed by the FSC, along with outdated technology, complicate transportation. Farms within a 20 km radius of mills have an advantage due to rail access, while distant farms face higher costs, relying on tractors and trucks. Though FSC subsidizes transportation, poor maintenance of access roads delays harvesting and transit, further burdening farmers. Rising input costs also strain their income and livelihoods.

6 Strategies to enhance sugar industry

The Fijian sugar industry must significantly change its trade practices, strategies, and methods to address macro- and micro-level issues and improve sugarcane production. To prevent declining output, interventions should include introducing new technologies, adopting modern farming techniques that integrate traditional knowledge, and hiring skilled experts to manage the industry.Additionally, it will be necessary to diversify local sugarcane farms and the products made from sugarcane while ensuring that the procedures used to diversify are environmentally sound. Similarly, certain policy actions to raise farmer trust in the sector are urgently needed for farmers to increase crop production. The parties concerned, especially the miller, should foster an environment where farmers are more economically motivated to increase their output. They must also consider other interventions, such as a quality-based payment system for increasing sugarcane crop production and logical methods for determining the price of a sugar-the amount of money paid to farmers for their produce as well as all other products and byproducts sold in the local markets.

Strengthening research and development is crucial for the industry's growth. The government can support system biodiversification, soil fertility management, optimization of nutrient and energy cycles, and efficient use of local resources while promoting resilience and sustainability in the sugar industry. Prioritizing community-led innovation and resource sharing among farmers is essential for creating a sustainable sugarcane agricultural system. Leveraging traditional knowledge can significantly enhance farmers' livelihoods and improve sector performance (Fig. 10). In addition to the advances in sugarcane cultivation, the sugar industry stands to gain significantly from recent biotechnological developments aimed at adding value to sugarcane waste. The lignocellulosic composition of sugarcane by-products, such as bagasse and tops, presents a promising opportunity for converting these materials into high-value products. Specifically, the cellulose and hemicellulose fractions of these by-products can be utilized as raw materials for producing second-generation ethanol, a more sustainable alternative to traditional fossil fuels [83]. Moreover, the fermentation of sugarcane waste can yield prebiotics and other bioactive compounds that have applications in the food and pharmaceutical industries [84]. This approach not only addresses the challenge of waste disposal but also enhances the overall sustainability of sugarcane production by diversifying the industry's economic output. Implementing biotechnological processes to extract value

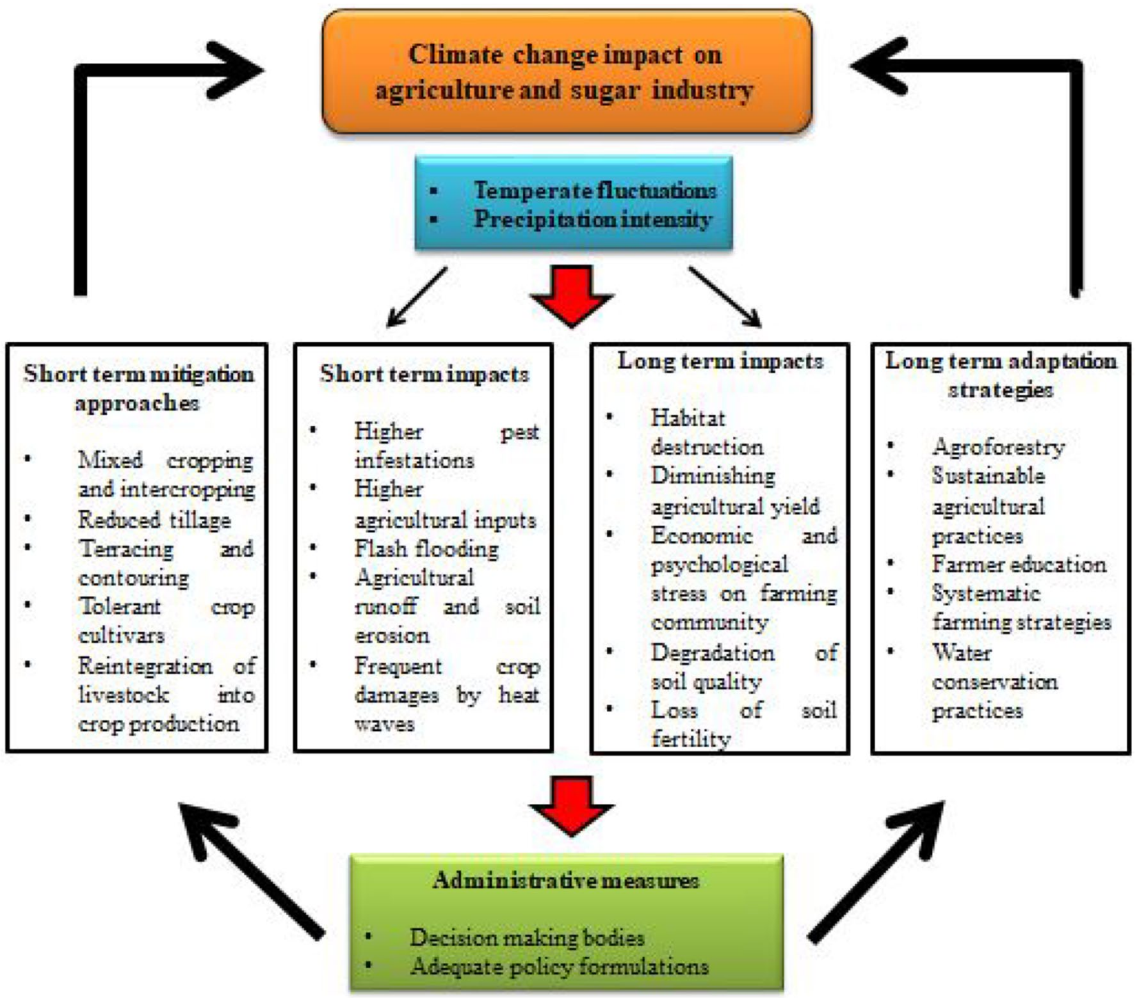

Fig. 10 Schematic representation of potential impacts of CC on agriculture/sugar industry and management strategies. Source [Created by author]

from sugarcane wastes can lead to a circular economy within the sugar industry, contributing to both environmental sustainability and economic viability [85]. As such, exploring these possibilities could provide valuable insights into the potential for improving resource efficiency in the sugar industry, aligning with global sustainability goals. The integration of biotechnological advancements with traditional sugarcane practices may pave the way for a more resilient and economically diverse industry, reinforcing the need for further research in this area.

7 Potential prospects and scope of C sequestration and sustainability in Fiji sugarcane

The term "soil C sequestration" refers to the storage of C in soil organic matter after plants absorb it from the atmosphere. The aim is to increase SOC density, enhance its depth distribution, and stabilize SOC by encasing it in stable microaggregates to protect it from microbial decomposition or as resistant carbon with a slow turnover rate. Regulating agroecosystems is a key strategy for SOC sequestration. Agriculture represents human-driven manipulation of C through its intake, fixation, emission, and transfer among various pools. Therefore, changes in land use and the adoption of recommended management practices are vital for effective SOC sequestration. This review explores the mechanisms by which sugarcane can facilitate the transfer of C from the atmosphere to the soil, followed by a detailed examination of current techniques in sugarcane C sequestration.

7.1 Plantstone C

Recent research has highlighted a natural process in plants, particularly in sugarcane, that plays a vital role in reducing CO_2 emissions and mitigating global warming. This process involves plantstone C, also referred to as phytolith-occluded C [86]. The plantstone C has been successfully trapping 300 million tonnes of CO_2 yearly from the atmosphere and burying it beneath the soil for countless years. Plant leaves, especially grassy plants like wheat and sugarcane, contain minute silica grains that coalesce to form plantstones [87]. A small amount of OC becomes contained within the minute silica grains while the plant grows [17]. The C stored in plantstone is resistant to degradation, remaining intact even after the plants die, burn, or are harvested. As a result, plantstone effectively sequesters CO_2 from the environment, unlike other plants that readily decompose and release CO_2 back into the atmosphere. This highlights the potential for farmers' crop selection decisions to significantly impact CO_2 removal from the atmosphere. [88] estimate the sugarcane crop's PhytOC yield was 18.1 g C m^{-2} $year^{-1}$. Thus, 181 kg C has been sequestered ha/year. In another study, [89] estimated this procedure extracts about 300 Mt of CO_2. Sugarcane is a champion crop for C sequestration, according to some plantstone studies [90, 91]. Growing sugarcane provides farmers with benefits beyond sugar production; by storing more C in the abundant plantstones produced, they can also deliver environmental services. Altering the crops that farmers cultivate is not the only way to enhance C absorption by plantstones. For sugarcane farmers, selecting one variety over another can lead to an additional 0.25 tonnes of CO_2 being sequestered per hectare per year in the soil through plantstones. The C occluded in PhytOC is very resistant to breakdown compared to other SOC fractions that do so over a considerably shorter time frame [92]. Plantstone C presents an effective opportunity for land managers to further reduce CO_2 emissions and contribute to combating global warming. The discovery of phytoliths is both intriguing and timely. It is crucial for farmers to engage in the development of C markets by demonstrating that C can be permanently and measurably sequestered in the soil. This positions plantstone as a potential source of revenue, which could be recognized in future C trading programs.

7.2 Sugarcane residue retention

Sugarcane, a perennial grass, is grown economically and commercially in over 90 countries, with a total global area of about 26 106 ha and an annual production of 1.83 billion tons [93]. In many countries, burning sugarcane leaves and debris for faster harvesting is an unsustainable practice that releases GHGs, particularly CO_2. Additionally, burning leaves and litter puts soot and charcoal into the environment, which is unhealthy [94]. Burning residues after each harvest are being replaced in many sugarcane-producing areas by leaving the residues on the soil's surface instead. At harvest, mature sugarcane crops produce substantial amounts of residues (also known as trash; 13–20 t DM ha), which are rich in C (42%) and reasonable amounts of plant nutrients (0.46–0.54% N, 0.47–0.66% K, 0.09–0.17% Mg, 0.18–0.41% Ca, 0.06–0.17% S, and 0.05–0.09% P) [95, 96]. Keeping sugarcane residues instead of burning them offers several benefits, such as improving soil quality, enhancing C absorption, reducing fertilizer needs, and decreasing air pollution [97]. Research indicates that composting sugarcane waste improves the soil's physical, chemical, and biological properties compared to burning [98]. Unlike the traditional burning method, leaving sugarcane residues in the soil enhances biological activity, reduces bulk density, improves soil aggregation stability and penetration rate, and lowers gas emissions [99]. Studies have shown that retaining sugarcane crop residues as opposed to burning them may result in an increase in the total amount of OC in the soil, such as by 2 g kg^{-1} (0–200 mm) after 6 years [96], 5 g kg^{-1} (0–200 mm) after 8 years [98], or 9.2 g kg^{-1} after 55 years [100]. [101] reported that a farm where the trash and residues were left on the soil had a 30% lower C content in terms of particle organic matter and microbial biomass C than one where they were burned. The overall C stocks were higher in unburned treatments. In Sao Paulo State, 14 years of green-trashing increased soil organic C stocks under the 0.1 m layer by 0.93 tons C ha^{-1} yr^{-1}, according to research by [102]. Heavy sugarcane biomass in both the upper and lower soil layers can act as significant reservoirs for C sequestration, enhancing efforts to mitigate CC.

7.3 Conservation tillage

The sugarcane production system has undergone significant changes over the past few decades, shifting from manual harvesting to a green mechanized collection system. This green harvesting approach is considered beneficial for agronomic and environmental factors [103]. However, increased machinery activity during automated harvesting and transportation has led to soil compaction, a major issue in sugarcane farming [104]. Traditionally, soil tillage is conducted before planting to alleviate this compaction. Tillage disrupts soil aggregates and exposes the SOM to microbial respiration, consequently increasing soil C losses by CO_2 emissions to the atmosphere [2]. Recent research, however, suggests that the advantages of soil tillage are transient and, after one or two years of sugarcane production, are no longer discernible [99]. In contrast, using conservation tillage (like reduced tillage) in place of conventional tillage protects the soil's physical quality in annual crops since soil disturbance is limited to the planting row and the majority of the soil surface is still covered with crop residues [105]. Numerous studies indicate that conservation tillage enhances soil biological activity, nutrient cycling, C sequestration, erosion protection, and crop production. However, the extent of these benefits, particularly regarding C sequestration and crop yield, varies based on climate, soil characteristics, and the adoption of other best management practices [15, 16].

Despite the recognized benefits of conservation tillage, conventional tillage remains the dominant practice in Fiji's sugarcane fields. The main challenges to adopting conservation tillage include managing soil pests and weeds, addressing soil acidity, and alleviating compacted soil issues. According to a previous study, most of the soil C accumulated during the sugarcane cycle in green cane lands is lost following tillage operations during the replanting season [106]. [106] revealed that 3.5 Mg CO_2 ha^{-1} was removed from the soil after soil tillage for reforming sugarcane fields. On the other hand, using conservation tillage techniques led to a soil C accumulation rate of 0.96 to 1.11 Mg ha^{-1} $year^{-1}$, showing that this method may be a workable way of increasing C sequestration in sugarcane soils [107]. Sugarcane conservation tillage is a form of reduced tillage since the planting furrow, which is produced once every five years, disturbs around 13% of the soil layer (up to 40 cm) [108]. The introduction of new technologies, such as controlled traffic systems and transplanting pre-sprouted seedlings, should significantly reduce soil disturbance during sugarcane planting. This will enhance the potential for soil C accumulation and help minimize GHGE's. Additionally, removing tillage techniques from sugarcane planting reduces the use of fossil fuels and indirectly lowers GHGE's [109].

7.4 Sugarcane bagasse biochar

There is a great deal of interest in research surrounding biomass conversion into value-added products like biochar and biofuel. Rising energy needs, worries about GHGE's, and global soil deterioration are all responsible for this [110]. Biochar is a fine-grained, porous C- naceous substance made from animal, urban, and agricultural waste that is pyrolyzed at temperatures between 350 and 600 °C without oxygen [111]. It improves soil fertility by acting as a soil conditioner [112]. Biochar possesses unique physicochemical characteristics, including a high surface-area-to-volume ratio, the ability to store moisture, a stable aromatic C-skeletal structure, functional groups, trace elements, and the ability to absorb substances [113]. Previous studies have emphasized the advantages of biochar technology, especially in terms of C sequestration through biochar application to soil [114, 115]. Also, when utilized as a soil amendment, the other key characteristics of biochar are pH, water-holding ability, nutrient content, elimination of pollutants, and cation exchange capacity [116]. Sugarcane bagasse is regarded as the material leftover after cane juice has been extracted from sugarcane. Bagasse, like most agricultural wastes, is biomass rich in C, plentiful, and appropriate for the generation of biofuel or biochar. Fiji sugarcane has the potential to produce over 312,000 tons of cane bagasse each year. Bagasse could also be used as a source of biofuel through anaerobic digestion [117]. Bagasse is a complex lignocellulosic material that typically contains 50% cellulose, 25% hemicellulose, and 25% lignin, along with additional substances such as pentosans, cellulose, and inorganic substances known as ash [118]. Sugarcane bagasse biochar, produced through pyrolysis, is an environmentally friendly and durable adsorbent material. It has been shown to enhance total theoretical recoverable sucrose (TRS), as well as cane and sugar yields. Increases in soil C, better drainage and aeration, and the provision of nutrients for the sugarcane crop are all advantages of applying biochar to cane fields [119]. [120] found that biochar significantly improved the net photosynthetic rate throughout all developmental stages while reducing transpiration. Its application positively affects sugarcane growth, photosynthetic traits, and nutrient uptake, benefiting agronomy and water quality in cane fields. [121] reported that biochar amendments increased cane yields by 22% in slit loam and 12% in clay soils. Additionally, biochar reduced total suspended particles, biological oxygen demand, and nutrient losses in runoff from both soil types. The leaching of cation nutrients was reduced, and SOC was increased by biochar. Sugarcane bagasse biochar product retains a significant portion of nutritional bagasse value. Cane fields can receive C from this for long-term C sequestration and potential future C credits. Following the application of different biochar products, nitrous oxide and other GHGE's from agricultural fields can be significantly reduced [122].

7.5 Integrated nutrient management (INM)

Today's sugarcane is recognized as an aneuploid hybrid crop developed through the Nobilization process from a cross between *Saccharum officinarum* L. and a wild relative *Saccharum spontaneum* [123]. Long-term cultivation of high biomass crops like sugarcane is crucial for enhancing soil quality, as it regulates the physical, chemical, and biological properties of the soil, which control nutrient and moisture dynamics and root behavior. However, sugarcane production often relies on ratooning—growing a succeeding crop from the stubble of a previous one- nto reduce costs associated with seeds, planting, and land preparation [11]. An integrated approach is essential for enhancing long-term soil productivity. To promote a more productive, economic, and environmentally friendly farming system, it is vital to address the growing nutrient demands of intensive sugarcane cultivation while improving the resource base's overall quality. INM offers significant potential in this regard. By simultaneously utilizing organic manures and inorganic fertilizers, INM is recognized as an efficient method for maintaining healthy, sustainable soil systems and boosting crop yields [124]. It enhances and maintains soil fertility and offers a strong foundation for agricultural production systems to adapt to changing demands [125]. To preserve a healthy soil's physical and chemical environment and to act as an energy source for the biomass of soil-microbial organisms, it is crucial to utilize organic, inorganic, and biofertilizers in moderation. INM is one of the methods for increasing yields and restoring SOC in depleted and degraded soils. Sugarcane requires a significant quantity of nutrients from the soil for optimal growth and development since it is a crop with a long growing season and an exhaustive crop. About 140 kg N, 34 kg P and 332 kg K may be removed from the soil by a crop of 100 tonnes of cane yield [126]. In addition, significant nutrients are lost due to leaching, denitrification, volatilization, etc. It is crucial to add organic manures and inorganic fertilizers at the right time and in the right balance to replenish these nutrients. Adding organic wastes in the form of root biomass contributes to a noticeable increase in the physical and microbiological qualities of the soil [127]. According to [14], the sequestration of sugarcane-derived C from long-term cane production was sufficient to make up for the losses in native SOC stock. In a study, [128] revealed that integrated use of FYM @25% of the recommended dose of N (RDN) with RDF (250–125-125 kg N-P-K/ha) and biofertilizer (Azotobactor and phosphate solubilizing bacteria (PSB) to plant crop followed by 10 t/ha trash incorporation with bio-fertilizer inoculation + RDF (300–6.25–125 kg N-P-K/ha) application increased cane (13.3 to 30.6 t/ha) and commercial cane sugar (0.5 to 1.6 tonne/ha) yield. [129] found that applying organic manure (FYM or PM/PMC or GM) + N 1/2 P or NP or NPK increased the SOC% over NPK, from 0.39 up to 0.52% and 0.44 up to 0.48% in two consecutive experiments. To maintain a healthy physical and chemical environment, support microbial biomass, and ensure sugar yield, a balanced application of organic, inorganic, and biofertilizers is essential. Research indicates that combining inorganic and organic manures, rather than using them separately, enhances the sustainability of sugarcane and sugar production [130]. This integrated approach not only sustains soil and crop productivity but also preserves soil health, enhances C storage, and helps prevent various nutrient deficiencies within the soil system [131]. [132] revealed that a combination of 350–375 kg N, 100–150 kg P_2O_5, 150 kg K_2O, and 50 kg $FeSO_4$ per ha, together with other inputs like bio-compost and bio-fertilizers, is recommended for ratoon sugarcane to improve the soil fertility status and promote nutrient uptake. In a 6-year sugarcane study, it was revealed that the application of organic fertilizers, including farmyard manure (FYM), bio-compost, and bio-methanated distillery effluent (BMDE), together with inorganic fertilizer (100% NPK), significantly enhanced the amount of millable cane, cane yield, and sugar output. [133] reported that the various pools of SOC, viz., soil microbial biomass C, water-soluble C, C storage, and CO_2 evolution, varied significantly due to different treatments. The BMDE-treated treatments had the maximum amount of soil organic pools (150 m^3/ha), followed by bio-compost (20 t/ha). Utilizing both organic and inorganic fertilizers together allowed for the accumulation of OC, which had a significant positive impact on the soil's C pool and fertility status (N, P, K, and S), as well as a beneficial reduction in bulk density for maintaining sugarcane plant productivity in a ratoon system. [134] revealed that as compared to using inorganic fertilizer alone, applying N via organic manure and biofertilizer together with chemical fertilizer enhanced growth characteristics, OC and available N, P_2O_5 and K_2O contents. Treatment T7 (75 percent recommended dose of N via inorganic + 25 percent recommended dose of N via FYM + Azotobacter + Azospirillum) revealed the highest cane yield (86.10 t/ha) and sugar content (17.52%). [135] reported that Treatment 3 viz., Poultry Litter (PL) at 5 t ha^{-1} + 95: 51: 87: 9: 10: 2.5: 4 kg N: P: K: S: Mg: Zn: B ha^{-1} were better productive and a promising integrated nutrient management technology for ensuring higher yields and quality of sugarcane without soil fertility degradation. Varying organic manure types can affect soil SOC and crop yields [136]. Total organic C (TOC) concentrations, especially in the short term, will not reflect such changes. To comprehend the dynamics of SOC at the early stages of management practices, such as INM, changes in more sensitive C fractions, such as dissolved organic C, microbial biomass C, readily mineralizable C, and particulate organic C, are crucial [137]. Integrating organic manures with chemical fertilizers sparingly could close the yield gap between actual and prospective yields [138] and increase soil C levels. Adopting the INM strategy and utilizing specific on-farm resources for rice farming could enhance soil quality and aid in sequestering various SOC fractions.

7.6 Crop rotation

Crop rotation in sugarcane involves alternating sugarcane with different crops to enhance soil fertility, disrupt pest cycles, and improve overall agricultural sustainability.. Crop rotation can improve the chemical and physical characteristics of the soil [139]. It is an additional agricultural strategy to lower GHGE's, interrupt the monoculture cycle, and enhance soil quality [140]. Although yearly crop rotation is difficult to perform because sugarcane is a semi-perennial crop, it is possible to grow other crops while sugarcane is being replanted every five years. Green manure legumes (such as *sunn hemp-Crotalaria* sp.) are favored to create a symbiotic relationship with N-fixing bacteria. Legume cover crops improve other aspects of soil health [141] and offer pertinent soil-related ecosystem services, such as a decrease in pest infestation, control of soil erosion, and a supply of N through biological N fixation, which lowers the need for N-fertilizer in the succeeding crop [142], reducing the associated nitrous oxide (N_2O) emissions and nitrate leaching. Compared to monoculture, crop rotation has several advantages, as evidenced by its capacity to increase SOC [143], particularly when a leguminous species is included in the crop rotation [144]. Legumes can improve soil fertility by adding SOM to the soil [145]. In contrast to non-leguminous crops with a larger C content, legumes have low C/N ratios and favor nitrogen (N) immobilization over N mineralization by soil microbes. Some N-efficient legume residue management techniques have been investigated to maximize the economic and environmental advantages of legume crop rotation in sugarcane cropping systems. For instance, research in subtropical Australia showed that no-till dramatically decreased N_2O emissions while yielding comparable sugar levels, as opposed to conventional tillage, when mixed soybean crop residues were in the soil before sugarcane planting [146]. [147] revealed that crop residue retention followed by soybean and peanut rotation improved overall soil microbial biomass and soil C mineralization capability in the sugarcane farming system. In Australia, sugarcane responds to legumes grown in rotation, resulting in yield increases of 15 to 25 percent [148]. Using a rotational crop is a crucial step to increase the sustainability of the soil–plant system, particularly when combined with the adoption of conservation tillage and preservation of soil covered with crop leftovers throughout the sugarcane cycle.

8 Conclusions

The Fijian sugarcane industry, a cornerstone of the nation's economy for over a century, is faced with significant decline in production falling over the past years. This downturn is attributed to a complex interplay of ecological, environmental, geopolitical, and socioeconomic factors, compounded by inadequate market development. The current challenges include CC, which has resulted in more frequent and severe weather events, particularly droughts, leading to increased instability for farmers. To safeguard the future of sugarcane cultivation in Fiji, it is imperative to adopt targeted and actionable strategies that will not only enhance production but also promote environmental sustainability. Policymakers should formulate and implement policies that support sustainable agricultural practices, including incentives for farmers who adopt climate-resilient crops and methods. Increasing funding for research and development on high-yield, climate-resilient sugarcane varieties and innovative farming techniques will be crucial for increasing productivity while minimizing environmental impact. Launching training programs aimed at educating farmers about sustainable practices such as conservation agriculture and integrated management practices can improve resilience against climate-related challenges. Collaborative efforts are critical to capture C from the atmosphere and sequester it in the soil, thereby mitigating CC impacts on agriculture. Implementing best management practices such as conservation tillage, utilizing sugarcane bagasse biochar, retaining crop residues, and incorporating crop rotations can enhance productivity and profitability. Furthermore, INM practices should be promoted to bolster soil health and crop yields. Safeguarding the sustainability of Fiji's sugarcane industry requires a holistic approach that integrates environmental considerations with agricultural productivity. Improving market access through the development of infrastructure and logistical support will enable farmers to receive fair prices for their products, encouraging them to remain in rural areas. Comprehensive life cycle assessments and integrated sustainability evaluations will be vital in ensuring that sugarcane production can thrive alongside ecological services and other land uses. Developing a framework for monitoring and evaluating the impact of implemented strategies will ensure that policies remain effective and adaptable to changing conditions. By fostering a resilient sugarcane production system, Fiji can navigate the challenges posed by CC while maintaining its agricultural heritage and securing a prosperous future for its farmers. By taking these concrete steps, policymakers and industry stakeholders can work collaboratively to revitalize the Fijian sugarcane industry, ensuring its sustainability and resilience in the face of ongoing challenges. This holistic approach will not only support farmers but also contribute to the overall economic stability of Fiji.

Acknowledgements The authors would like to acknowledge the encouragement from the members of the Crop Research Division, Ministry of Agriculture & Waterway (MOA & W), the Department of Crop Improvement, Sugar Research Institute of Fiji (SRIF), the Division of Soil Science and Agricultural Chemistry, Faculty of Agriculture, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, India and College of Agriculture, Fisheries and Forestry, Fiji National University, Fiji.

Author contributions "S.S.K. conceptualization; design and structure of manuscript; drawing figures; and writing original draft. S.S.K., K.K.G., O.A.W., S.S.H., S.K. and V.V.K. editing, critical revision. All authors read and approved the final manuscript.

Funding Not applicable.

Data availability No datasets were generated or analysed during the current study.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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