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IMPACT OF COVID-19 ON SUGARCANE YIELD IN THE TOP FIVE GLOBAL PRODUCING COUNTRIES

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ABSTRACT

The COVID-19 pandemic, which began in late 2019, caused severe disruptions to agricultural systems worldwide, and sugarcane production was among the sectors most affected. This article investigates the effect of the COVID-19 pandemic on the sugarcane output of the world's five leading sugarcane producers (Brazil, India, China, Thailand, and the US) from 1961 to 2023. Using panel data and fixed-effects models, the research analysed the effects of the pandemic, along with factors such as fertiliser, irrigation, pesticides, temperature, subsidies, and GDP per capita. Despite contradicting expectations, the results show clear evidence of COVID-19 having a significant direct impact on sugarcane production in most countries. The main results indicate that the use of fertilisers and pesticides is the major factor driving increased yield under diminishing returns. However, subsidies and GDP per capita indicate the positive impacts of input utilisation. The unexpected positive impact of the pandemic is attributed to labour transfers from urban to rural areas, increased government support for agriculture, and a greater focus on domestic food security.

KEYWORDS: Sugarcane Yield, Government Subsidy, COVID-19 Pandemic, Panel Data Regression

Sugarcane (*Saccharum officinarum* L.) is an essential industrial and agricultural crop that serves as the primary source of sugar and is also widely used for bioethanol production (Raza *et al.*, 2019). Brazil, India, China, Thailand, and the United States are the world's leading sugarcane-producing countries, collectively accounting for 73% of global sugarcane output (USDA, 2025). The economic significance of the crop extends beyond its direct consumption; it also creates many jobs, produces energy, and helps build rural communities. Nevertheless, the COVID-19 pandemic, first reported in late 2019, caused significant global destruction, and sugarcane production was one of the sectors hit hardest.

During the pandemic, the challenges in sugarcane farming were widespread and interconnected. The strict lockdowns and travel bans prevented the hiring of seasonal workers and migrant labourers, which caused delays in agricultural activities. These delays caused bottlenecks in the supply chain of fertilisers, pesticides, and machinery. The constraints also significantly affected market access, creating uncertainty around farm-gate prices and input costs. This problem was particularly evident in countries with a large sugarcane industry that heavily relies on labour hired for extended periods. Although some publications report specific impacts in certain countries, there are still not enough comprehensive comparative analyses that provide a view of the pandemic's effects in the major sugarcane-producing countries.

Previous research lacked the long-term historical perspective needed to assess the impact of COVID-19 on changing yields and the restructuring of agricultural systems. This study employs panel data regression analysis with EViews to assess COVID-19's impact on sugarcane yield among the top five global producers. The research assesses pandemic-related disruptions to sugarcane production and provides findings to help researchers, policymakers, and stakeholders improve sugarcane resilience against future global crises.

Trend of Sugarcane Yield

The trend in sugarcane yield, as shown in Figure 1, for the years 1961-2023, is an important factor in the agricultural sector; therefore, it is relevant to major sugarcane producers such as India, China, the United States, Brazil, and Thailand. The importance of yield in determining crop production cannot be overstated, as it is the primary factor in food security, economic stability, and environmental sustainability.

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The likelihood of yields increasing uniformly across all countries reflects the progress made in agricultural technology and plant breeding over the past 60 years. The rise in productivity has been vital in addressing the alarming increase in global demand for sugar and its by-products, including ethanol for biofuel. A higher yield not only indicates more efficient land use but also helps solve the increasing problems of urbanisation and climate change, which are shrinking arable land. The increase in yields in India, especially during the 1990s, demonstrates how yield improvements can significantly transform a country's agricultural landscape. India shows consistent growth across most areas and periods. A plausible explanation for this growth is that India has surpassed Brazil as the world's largest sugar exporter, helping the country boost its economy and generate jobs for millions of farmers. The 2020 monsoon season coincided with initial lockdown disruptions to labour mobility and fertiliser distribution, potentially explaining this slight change—a phenomenon documented in the FAO's 2021 case study on pandemic-induced input management shortages (HLPE, 2020). From 2019 to 2023, Brazil’s yields remained roughly the same as from 2015 to 2018. Connecting transportation bottlenecks and delayed pesticide imports to regional yield variations, though the 2023 rebound shows adaptive recovery.

Similarly, the rise in China's yields has not only strengthened its ability to meet domestic demand but also reduced its reliance on imports. China experienced strong growth from 2019 to 2023 before COVID-19; yields remained high and stable, with no significant drop. This resilience aligns with findings on China's strong agricultural supply chains during lockdowns, supported by government-led logistics and digital farming technologies. The observed increase in yield in the United States highlights the benefits of sustained investment in research and development. The United States shows a steady upward trend from 2007 to 2018, and from 2019 to 2023, yields slightly increase - no evident decline occurs during that period, COVID-19. This consistency indicates that highly mechanised production systems are less vulnerable to labour shocks, supporting USDA (2022) reports of minimal operational impact from COVID-19 on large American farms.

The data from Thailand, characterised by high variability and recent sharp fluctuations, highlight that another essential aspect of yield importance is resilience. The ability to compensate for or quickly replace losses in high-yield crops caused by factors such as weather, insects, or diseases is essential for stabilising food supplies and economic planning (Msomba *et al.*, 2024). Between 2019 and 2021, yields fell sharply but then recovered by 2022-2023, showing a varied outcome in Thailand. This indicates that Thailand's yields were affected by COVID (or other concurrent factors such as weather, logistics, or inputs). This may reflect favourable weather conditions and Thailand's strategic focus on export-oriented commodities, which are less affected by domestic restrictions. In a nutshell, the COVID-19 period did not cause a general global yield decline, but Thailand’s yield trend indicates it may have been disproportionately affected.

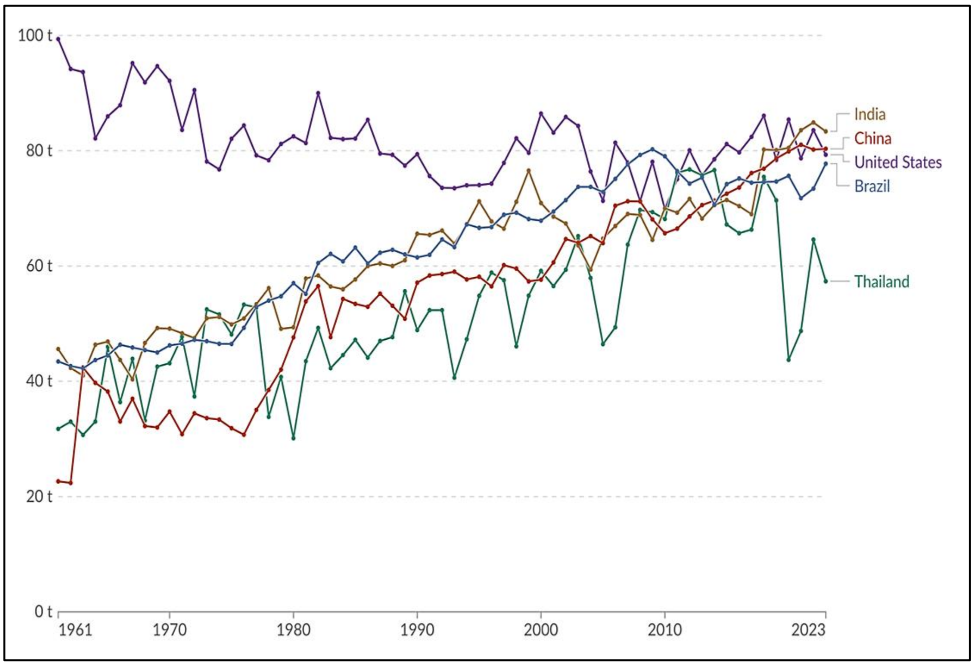

Figure 1: Long-term trends in sugarcane yield from 1961 to 2023 across five major sugarcane-producing countries

METHODOLOGY

Data Collection

This study uses secondary data from reputable international sources to ensure the reliability and validity of the findings. Data sources include the Food and Agriculture Organisation of the United Nations (FAO), which provides annual data on sugarcane yield (tons per hectare), fertiliser use (kilogram per hectare), pesticide use (kilogram per hectare), irrigation (percentage of total water withdrawn for agriculture), and temperature changes (annual land temperature changes in degrees Celsius). The Organisation for Economic Co-operation and Development (OECD) provided information on government subsidies as a percentage of gross farm receipts, and the World Bank offers data on GDP per capita. The dataset covers the period from 1961 to 2023, providing 63 annual observations per country (a total of 315 across all countries). This long-term time series allows for trend analysis over decades, especially during the COVID-19 period (2019-2023). Sources in this study provide datasets on key global indicators of sugarcane production, ensuring broad geographical coverage and consistent data over time, both of which are essential for longitudinal analysis.

Panel Data Regression

Panel data regression analysis is a statistical method for analysing two-dimensional panel data (typically cross-sectional and longitudinal). This technique is useful when working with datasets that include observations of multiple phenomena collected over different periods for the same individuals. Panel data models offer several advantages over traditional cross-sectional or time-series models, including greater sample variation, reduced collinearity among variables, greater degrees of freedom, and higher efficiency. The basic structure of a panel data regression model is shown in Equation 1.

$$Y_{it} = \alpha i + \beta X_{it} + \varepsilon_{it} \qquad \text{Eq. 1}$$

Where; $i = 1, \dots, N$ represents cross-sectional units, $t = 1, \dots, T$ denotes time periods, Y_{it} is the dependent variable, α is the intercept term, β is a $k \times 1$ vector of parameters to be estimated on the explanatory variables, X_{it} is a $1 \times k$ vector of observations on the explanatory variables, and ε_{it} is the error term.

The Fixed Effects Model was employed because it assumes that the entity's error term is correlated with the predictor variables and removes the effect of time-invariant characteristics to assess the net effect of the predictors on the outcome variable. In this study, we employed a fixed-effects model to better account for time-invariant differences across entities, enabling us to evaluate the net effect of the predictors on the outcome variable (Ren & Allison, 2024). Our specific model is shown in Equation 2.

$$SY_{it} = \alpha_i + \beta_1 Fer_{it} + \beta_2 Irri_{it} + \beta_3 Pest_{it} + \beta_4 Tem_{it} + \beta_5 Sub_{it} + \beta_6 GDP_{it} + \beta_7 CO_{it} + \varepsilon_{it} \qquad \text{Eq. 2}$$

Where SY = Sugarcane yield (total sugarcane output in tons/ha), Fer = Fertilizer (total number in kg/ha), $Irri$ = Irrigation (water withdrawn for agriculture as a % of the total water withdrawn), $Pest$ = Pesticide (total number in kg/ha), Tem = Temperature (temperature change on land in ℃), Sub = Government subsidy (% of gross farm receipt), GDP = GDP per capita (\$1000), CO = COVID-19 (dummy; 0 = before COVID and 1 = during COVID), thus, since CO is a dummy variable it was coded 0 for the pre-intervention period (1961-2018) and 1 for the post-intervention period (2019-2023). The dummy periods follow established econometric practice for modelling structural breaks with known timing. This specification effectively isolates country-specific effects while controlling for cross-sectional effects, as demonstrated in difference-in-differences analyses of policy interventions. The 2019 breakpoint was selected based on the pandemic, causing documented discontinuities in global economic indicators, ensuring the dummy captures exogenous structural shifts rather than endogenous fluctuations (Damiano *et al.*, 2024). α_i = Global producing country-specific fixed effect, ε_{it} = Error term, i = Global producing countries, t = Time (years). The panel data regression analysis was conducted using EViews 12, a statistical software package that offers a comprehensive set of panel data estimation techniques.

RESULTS AND DISCUSSION

Comparative Analysis - Sugarcane Yield Across Periods and COVID-19 Implications

Given the limitations of the COVID-19 period (4 time periods for this comparison), this study employs a descriptive-comparative approach. This method analyses trends over time periods to determine the indirect impacts of COVID-19 on sugarcane yield. Specifically, we compare yields in 4-year periods: 2019-2023 (COVID period) versus 2004-2008, 2009-2013, and 2014-2018 (pre-COVID periods). This helps us identify changes that may be caused by pandemic disruptions, such as labour shortages (e.g., migrant workers unable to travel), reduced access to inputs (e.g., fertiliser supply chain issues), and delays in farming activities.

Figure 2 shows the sugarcane yields (in tons per hectare) for Brazil, China, India, Thailand, and the United States (top five sugarcane producers) over 4-year periods, highlighting patterns that underline the indirect effects of the COVID-19 pandemic on sugarcane yields. This indicates mixed effects of the COVID-19 era on sugarcane yields among major producers from 2019 to 2023. Brazil's yield remains stable compared to earlier periods, demonstrating resilience in field operations and supply chains. China and India both show substantial improvements from 2019 to 2023 compared to 2014 to 2018, indicating enough input availability and mechanisation or weather advantages that surpassed the pandemic disruptions. The USA also edges upward, continuing a gradual long-term improvement, likely driven by technology and management efficiencies. On the other hand, Thailand shows a significant decline from 2019 to 2023 compared to earlier periods, indicating significant pandemic-related constraints such as labour shortages, logistics disruptions, or simultaneous drought, serious existing issues and vulnerabilities. Instead of a uniform global decline, the COVID-19 period shows divergence: some countries maintained or improved yields through strong systems and favourable conditions, while others, particularly Thailand, faced significant challenges.

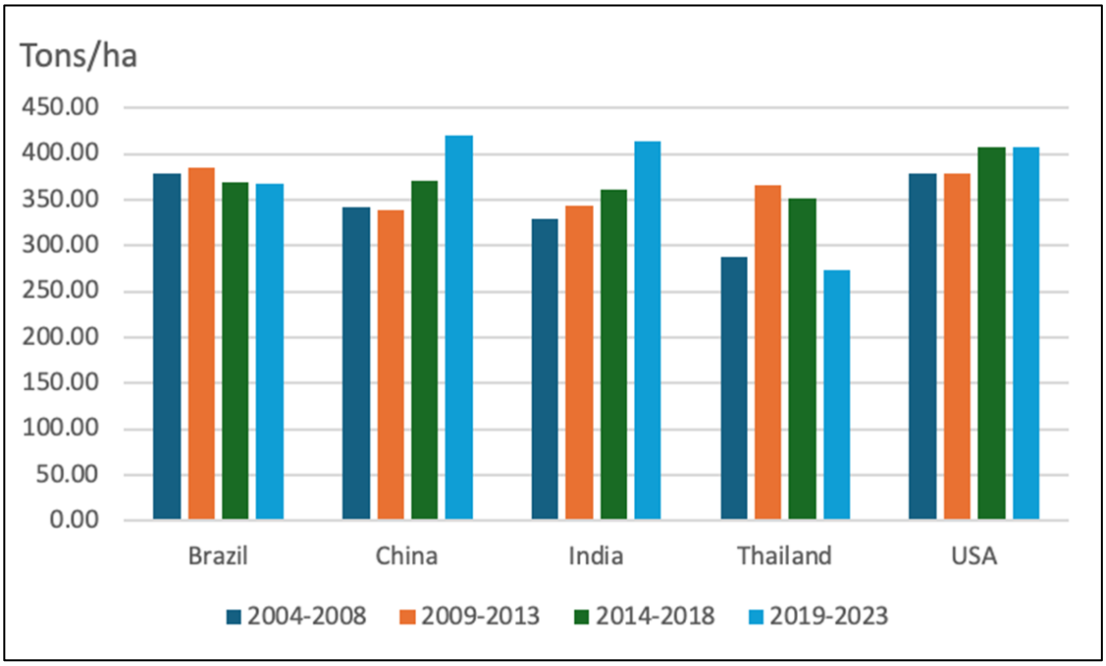

Figure 2: Sugarcane yield in top-producing countries across four time periods

Impact of COVID-19 on Sugarcane Yield in the Top Five Global Producing Countries

As shown in Table 1, the results of a multiple linear regression model illustrating the impact of COVID-19 on sugarcane yield in Brazil, India, China, Thailand, and the USA are presented. The analysis examines factors such as fertiliser use, temperature, GDP per capita, and a COVID-19 dummy variable (1 = during COVID-19, 0 = before COVID-19). The findings reveal the correlations and various influences present in these countries.

Brazil's model accounts for 92.08% ($R^2 = 0.9208$) of the annual sugarcane yield variance. The fertiliser application has a positive, statistically significant impact on yield, but the squared term is negative, indicating diminishing returns. This is consistent with the findings that applying fertilisers at high rates can negatively affect sugarcane yield (Bhatt, 2020). Again, temperature is a significant factor with a nonlinear relationship, as supported by the results on the climate effect on sugarcane yield. The COVID-19 variable is positively and significantly impacts sugarcane yield at the 5% level, indicating that sugarcane production increased during the pandemic period. Research has shown that social isolation in cities temporarily reduced people's movement to agricultural areas, potentially increasing the farming workforce and, in turn, sugarcane yield. Nonetheless, it contradicts expectations of negative effects resulting from supply chain disruptions and labour shortages (Zahraee *et al.*, 2022).

Table 1: Multiple linear regression results on the impact of COVID-19 on sugarcane yield in the top five global producing countries

Variable	Coefficient	Standard Error	P-Value
Brazil			
Constant	43.55780	1.041632	0.0000***
Fertilizer	0.979434	0.135720	0.0000***
Fertilizer^2	-0.008927	0.001256	0.0000***
Temperature	12.96525	2.903968	0.0000***
Temperature^2	-7484422	1.676472	0.0000***
GDP per capita	0.000192	0.000324	0.5551
COVID-19	9.314443	4.188623	0.0302**
Observation: 63 $R^2 = 0.9208$			
India			
Constant	44.44408	1.449625	0.0000***
Fertilizer	0.626628	0.055028	0.0000***
Fertilizer^2	-0.002798	0.000809	0.0011**
Temperature	-1.950783	2.349082	0.4099
Temperature^2	-12.89369	4.405196	0.0050**
GDP per capita	-0.010356	0.006166	0.0987*
Temperature × GDP per capita	0.014709	0.005449	0.0092**
COVID-19	10.47924	2.338070	0.0000***
Observation: 63 $R^2 = 0.9388$			
China			
Constant	38.18110	1.716139	0.0000***
Temperature	18.37099	4.723947	0.0003***
Temperature^2	1.566434	4.354454	0.7204
GDP per capita	0.000467	0.000159	0.0049**
Temperature × GDP per capita	-0.000276	0.000143	0.0594*
COVID-19	9.533311	5.470394	0.0868*
Observation: 63 $R^2 = 0.8131$			
Thailand			
Constant	38.66647	1.796489	0.0000***
Fertilizer	0.295195	0.151677	0.0567**
Fertilizer^2	-0.001386	0.002068	0.5055
Temperature	-8.785993	4.081147	0.0357**
Temperature^2	3.208532	3.111537	0.3069
GDP per capita	0.004060	0.001358	0.0041**
COVID-19	-19.83221	5.586021	0.0008**
Observation: 63 $R^2 = 0.7466$			
USA			
Constant	99.30985	2.619909	0.0000***
Fertilizer	-0.443556	0.069075	0.0000***
Temperature	0.610137	2.399015	0.8001
Temperature^2	2.259563	1.428619	0.1192
COVID-19	4.829824	2.324214	0.0421**
Observation: 63 $R^2 = 0.4987$			

***, ** and * are significant levels at 1%, 5% and 10% respectively

India's model has the highest explanatory power among the five countries ($R^2 = 0.9388$). The fertiliser application coefficient is similar to Brazil's: it has positive effects and shows diminishing returns. Temperature has a significant negative quadratic effect, indicating that extreme temperatures may harm sugarcane yield. The interaction between temperature and GDP per capita is positively associated with sugarcane yield—unlike China's findings—suggesting an opposite effect. The COVID-19 variable is significant and positive, showing that yield increased during the pandemic. This might point to the measures taken by the government, for instance, the INR 1.7 trillion agricultural stimulus program, which was mainly aimed at sugarcane procurement.

China's model explains 81.31% ($R^2 = 0.8131$) of the variation in sugarcane yield. Temperature, as one factor, appears to significantly affect yield outcomes, while GDP per capita is also a contributing factor. The relationship between temperature and GDP per capita is significant and negative, indicating that as GDP per capita increases, the positive impact of temperature on yield decreases. This interaction supports the findings of (Bhatti *et al.*, 2024) on the relationship between economic factors and climate impacts in agriculture. The COVID-19 variable is positive and significant at the 10% level, indicating a rise in sugarcane yield during the pandemic.

Thailand's model accounts for 74.66% of the yield variation. The fertiliser has a limited but positive effect, while temperature shows a significant negative linear relationship. GDP per capita has a significant positive impact. Interestingly, in our study, Thailand is the only country with a COVID-19 variable that is negative and significant, indicating a decrease in yield during the pandemic. This closely aligns with the predicted negative impacts of COVID-19 on agricultural output (Santosa *et al.*, 2023).

The USA's model accounts for 49.87% ($R^2 = 0.49.87$), which may be due to fewer variables included in the model. The fertiliser application coefficient was surprisingly inversely related to yield, despite generally reported trends in other countries and some literature, as well as disagreements among researchers. This finding may suggest excessive fertiliser application or other unknown factors affecting the U.S. sugarcane yield. The COVID-19 variable shows a positive, significant impact at the 5% level, suggesting that yield increased during the pandemic. This could be associated with federal aid programs, such as the CARES Act, which directly affected agribusiness liquidity.

Impact of COVID-19 on Sugarcane Yield in the Four Global Producing Countries

Because complete subsidy data for Thailand from 1961 to 2023 were unavailable, we excluded Thailand from this analysis and instead focused on the top four countries. As shown in Table 2, the R^2 value of 0.8149 explains roughly 81.49% of the variation in sugarcane yield.

The report shows a significant positive effect of COVID-19 on sugarcane yield, with a coefficient of 8.500398 ($p < 0.001$). Several findings align with our results. In areas like Acadiana, the sugarcane harvest in 2020 performed well, exceeding the 5-year average due to ideal weather conditions (ample rainfall and sun, minimal winds) that coincided with the pandemic. After initial disturbances in 2020-2021, a strong recovery was observed in 2022, driven by significant yield increases in regions such as Tamil Nadu and Maharashtra (Veerbhan & Malik, 2025). Sugar production in Fiji was 22% higher in 2022 than during the same period in 2019 (Sachan & Krishna, 2021). This was quite unexpected and contradicts the expectations and findings of other studies. For instance, the adverse effects of the pandemic on sugarcane production, including labour shortages, supply chain disruptions, and reduced demand (Patil *et al.*, 2024). Much research has found that during the pandemic, global food security and agricultural output were heavily impacted. However, the beneficial outcome identified in this research might also be explained by factors such as increased focus on local agriculture and nutrition security during the outbreak, as well as changes in the labour market, such as city workers moving to the countryside or urban areas (Saripalle & Chebolu-Subramanian, 2024). Such alterations may result from changing global trade patterns that favour local production and the need to adjust agricultural policies to address the pandemic. The pandemic shifted the sugarcane trading system from a contractual to a free-market model in some areas, which was found to be more efficient under those conditions, potentially leading to better farmer outcomes and, in turn, stronger production incentives (Thibane *et al.*, 2023). Labour shortages during the pandemic highlight the need for more mechanisation, leading to a focus on new technologies and efficient farming practices to improve long-term sustainability and yield (Sridhar *et al.*, 2023).

The coefficient for fertiliser indicates that if fertiliser application increases by 1 kg/ha, the sugarcane yield will increase by 0.13069 tons/ha, assuming other variables remain constant. This finding reveals a positive correlation between fertiliser use and sugarcane yield, consistent with general agronomic principles and supported by many studies. For instance, Ahmed *et al.* (2024) noted that it was the application of balanced fertiliser, which was the main reason for the increase in sugarcane yield.

The irrigation coefficient indicates that, holding all other variables constant, a 1% increase in irrigation results in a 1.67675 tons/ha decrease in sugarcane yield. This indicates the possibility of waterlogging or inefficient irrigation, suggesting that irrigation may exceed the actual needs requirement. According to (Khonghintaisong *et al.*, 2021), access to adequate water during the growth period acts as a key regulator of sugarcane's physiological processes, thereby improving the growth rate, stalk length, and sugar accumulation. One of the main benefits of irrigation is reducing the negative effects of drought and unpredictable rainfall, helping producers achieve a steady, profitable sugarcane harvest (Ncoyini *et al.*, 2022).

A positive pesticide coefficient indicates that for every 1 kg/ha of pesticide applied, sugarcane yield increases by 5.82959 tons/ha, assuming other factors remain constant. Nevertheless, the squared term, which is negative and significant, indicates that this positive effect diminishes at very high levels of pesticide use; therefore, optimal use is the key factor (Möhring *et al.*, 2020).

Subsidy significantly impacts sugarcane yield, meaning that a 1% increase in subsidy results in a 0.00805 ton/ha rise in yield, all other factors remaining constant. Studies support a positive relationship, noting that government support, including subsidies, has contributed to increased sugarcane yields (Rajput & Venkataraman, 2024). Sugarcane yield can be improved through government-supported nutrient management programs, mainly through subsidies (Bjornlund & Bjornlund, 2025). Nevertheless, some studies oppose this view or complicate it further in their explanations. Government subsidies in agriculture have caused inefficiencies and may not always result in increased yields (Kumbhakar *et al.*, 2023).

Table 2: Panel data regression results on the impact of COVID-19 on sugarcane yield in the four global producing countries

Variable	Coefficient	Standard Error	P-Value
COVID-19	8.500398	1.249335	0.0000***
Fertilizer	0.130692	0.067364	0.0547**
Fertilizer^2	-0.000411	0.000286	0.1534
Irrigation	-1.676748	0.837811	0.0476**
Irrigation^2	0.011167	0.006304	0.0790*
Pesticide	5.829587	1.026756	0.0000***
Pesticide^2	-0.556259	0.087785	0.0000***
Temperature	1.491427	0.194209	0.3624
Subsidy	0.008053	0.003839	0.0380**
GDP per capita	-0.000348	0.000109	0.0018**
Fertilizer × GDP per capita	0.000012	0.000007	0.0304**
Temperature × GDP per capita	0.000122	0.000415	0.0040**
Cross-Section Fixed Effects			
Country	***Effects***		
Brazil	113.3816		
China	102.6511		
India	116.0299		
USA	110.8262		

***, ** and * are significant levels at 1%, 5% and 10% respectively

R^2 = 0.8149

The GDP per capita coefficient shows that $1000 increase in GDP per capita will lead to a 0.00035 ton/ha rise in sugarcane yield, all other factors remaining constant. The correlation between GDP per capita and sugarcane yield has been widely studied in the context of industrialisation and urbanisation. Some studies suggest that the two are negatively correlated because industrialisation and urbanisation shift focus away from agricultural fields (Nisar *et al.*, 2021). Thus, higher GDP per capita led to a decline in sugarcane productivity because labour shifted out of agriculture. They observed that economic growth constrained the expansion of sugarcane yields due to competition for land use. Other studies oppose this development, such as distinguishing that higher GDP per capita improves sugarcane yields through better technology adoption (Agarwal *et al.*, 2025), and emphasising that economic growth enhances agricultural productivity through infrastructure investments (Rada *et al.*, 2019). Studies used R&D as a proxy for GDP per capita and demonstrated that R&D spending strongly correlates with yield improvements in sugarcane and other crops (Nin Pratt *et al.*, 2023).

The interaction term indicates that the country's GDP per capita influences the relationship between fertiliser use and sugarcane yield. This means that the impact of fertiliser use and temperature on soybean yield depends on per capita GDP. Therefore, in countries with higher GDP per capita, fertiliser application in sugarcane is likely to be stronger (Thibane *et al.*, 2023). The interaction term between climate variables and per capita GDP increases crop yields.

CONCLUSION

This research analysed factors influencing sugarcane yield in the major sugarcane-producing countries from 1961 to 2023 using fixed-effects regression, revealing unexpected results. Instead of the negative impact it was usually believed to cause, COVID-19 had a positive effect on yield, likely due to labour shifts to the countryside and government support. Fertilisers and pesticides are the major agricultural inputs that demonstrated the most significant positive effects; however, they indicate diminishing returns. Government subsidies also impact yield. GDP per capita included interaction terms, indicating that some countries were more productive and better able to adapt to the climate than others. The findings show that strategically allocating resources like inputs, subsidies, and climate adaptation efforts can boost productivity. The focus of future research should be on the long-term impacts of COVID-19 and the environmental sustainability of intensive farming practices.

Recommendation

Agricultural stakeholders should adopt precision agriculture techniques to optimise fertiliser application rates, especially in Brazil and India, where excessive use can decrease yields. This may involve soil testing, GPS-guided equipment, and variable-rate technology to apply fertiliser more efficiently, lowering costs and environmental impact while maximising sugarcane production.

Researchers and stakeholders should develop climate-resilient sugarcane varieties and invest in irrigation infrastructure to reduce temperature extremes. More efficient irrigation systems, such as drip irrigation or precision sprinklers, should be adopted, along with water management practices to optimise water use. This could help increase yields while conserving water resources. Brazil should prioritise heat-resistant strains, especially given the model’s high heat sensitivity. It may also be beneficial to invest in climate-resilient sugarcane varieties and adopt adaptive farming practices. These could include adjusting planting dates, enhancing irrigation systems, and using climate forecasting tools to guide crop management decisions.

Policymakers in Thailand should create contingency plans and build resilient supply chains to manage future pandemics or similar disruptions better. This might involve diversifying markets, investing in automation and digital technologies, and developing flexible labour-management strategies to maintain productivity during crises.

The government should consider increasing subsidy allocations, especially targeting small and marginal farmers to ensure fair benefits in Brazil, India, China, and the United States. Investing in research and development for better sugarcane varieties, along with training programs on best farming practices, will further boost productivity. Improving infrastructure for infrastructure and market access, along with measures to stabilise sugarcane prices, will help ensure fair compensation for farmers.

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DATA AVAILABILITY STATEMENT

The original analysed data presented in the current study can be requested from the corresponding author for any further inquiries.

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