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Research Article

Evaluation of Aajivi Nano Carb Formulated Using ISA Technology as a Soil Amendment for Improving Growth, Yield and Soil Health in Sugarcane

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Abstract

A field experiment was conducted at Dabhan village, Kheda district, Gujarat, India, to evaluate the effect of organic manure on growth, yield, juice quality, nutrient uptake, and soil health of sugarcane (*Saccharum officinarum* L.). The experiment was carried out in a Randomized Block Design (RBD) comprising two treatments, namely organic manure treatment and an untreated control, with three replications. The organic manure was developed using ISA Technology and enriched with the biodecomposer *Bacillus subtilis* (NCBI GenBank Accession no. QB017572). Organic manure application improved crop establishment and vegetative growth, with bud germination increasing from 84.36% to 94.28%, plant height from 281.84 to 318.46 cm, tillers per clump from 9.86 to 12.84, and millable canes per clump from 9.24 to 11.84 compared with the untreated control. The treatment increased cane yield from 89.82 to 112.46 t/ha and sugar yield from 10.29 to 14.43 t/ha, along with improved juice quality, as indicated by higher Brix, Pol, purity, and CCS values compared with the untreated control. Nutrient uptake of nitrogen, phosphorus, and potassium increased under the organic manure treatment. Soil organic carbon increased from 0.56% to 0.78%, while the microbial population increased from 5.24 × 10^6 to 8.62 × 10^6 CFU g^{-1} soil. Overall, organic manure improved sugarcane growth, productivity, juice quality, nutrient uptake, and soil health.

Keywords: Sugarcane; ISA Technology; Gujarat

Introduction

Sugarcane (*Saccharum officinarum* L.) is an important commercial crop grown in tropical and subtropical regions [1]. It contributes nearly 80% of global sugar production and is also used for ethanol, jaggery, bioenergy, paper, and animal feed [2]. In India, sugarcane occupies a major place in the agricultural economy and supports rural livelihoods and agro-industries [3]. However, maintaining high cane yield and juice quality is difficult because the crop has a long growth duration and a high demand for water and nutrients [4].

Sugarcane is a nutrient-demanding crop that requires a continuous supply of essential nutrients throughout its growth cycle. It removes substantial amounts of nitrogen, phosphorus, potassium, and other nutrients from the soil [5]. Ensuring a continuous and adequate supply of essential nutrients throughout the crop growth period is critical for maintaining high sugarcane productivity. Although chemical fertilizers have played a major role in enhancing crop growth and yield, their prolonged and excessive application has raised concerns regarding soil fertility, environmental quality, and the long-term sustainability of agricultural production systems [6].

Prolonged and excessive fertilizer application, particularly under monocropping systems, can adversely affect soil quality by depleting soil organic carbon, altering soil structure, and reducing biological activity [7]. Excessive nitrogen inputs can alter soil nutrient equilibrium and enhance nitrogen losses through processes such as leaching, surface runoff, and volatilization [8]. These losses reduce nutrient utilisation efficiency and can gradually reduce soil fertility and productive capacity. As a result, implementing effective and sustainable nutrient management strategies is critical for maintaining crop output while preserving soil fertility and long-term soil health.

Carbon-rich organic soil amendments have received increasing attention as a sustainable option [9]. They improve soil physical, chemical, and biological properties and increase soil organic carbon. Higher organic matter improves aggregation, water-holding capacity, and cation exchange capacity, while also supporting root growth and nutrient uptake [10]. It also stimulates beneficial soil microorganisms that aid decomposition, nutrient mineralization, and nutrient cycling [11]. As a result, these amendments can improve soil resilience and support long-term crop productivity.

The effectiveness of carbon-rich organic amendments is closely associated with their influence on soil biological processes. A biologically active soil supports diverse microbial communities that regulate nutrient transformation and availability within the rhizosphere [12]. Beneficial microorganisms such as *Azotobacter, Azospirillum, Bacillus, Pseudomonas, Rhizobium,* and *Trichoderma*, together with arbuscular mycorrhizal fungi, perform several essential ecological functions [13]. These microorganisms contribute to biological nitrogen fixation, phosphorus solubilization, nutrient mobilization, decomposition of organic residues, and the production of plant growth-regulating compounds [14]. Their activities improve nutrient availability and promote efficient nutrient uptake by plants. They also stimulate root growth, enhance root architecture, and increase the plant's ability to absorb water and mineral nutrients [15]. Collectively, these processes improve crop growth, strengthen soil biological activity, and help maintain long-term soil fertility.

The benefits of carbon-rich organic amendments are particularly important in sugarcane cultivation because of the prolonged growth duration and high nutrient requirement of crop [16]. Sustained vegetative growth and continuous biomass accumulation are dependent on the efficient availability of nutrients throughout the cropping period, whereas enhanced soil organic carbon stimulates microbial activity, thereby accelerating nutrient transformation within the rhizosphere [17].

Consequently, essential macro- and micronutrients become more readily available for plant uptake. Improved nutrient availability supports chlorophyll synthesis, photosynthetic efficiency, biomass production, and cane development [18]. At the same time, enhanced root growth enables the crop to explore a larger soil volume for water and nutrient absorption [19]. Increased soil organic carbon also improves soil aggregation, moisture retention, aeration, and nutrient-holding capacity. These improvements reduce nutrient losses and create favourable conditions for sustained crop productivity [20]. Therefore, carbon-rich soil amendments have emerged as promising components of sustainable nutrient management programmes for sugarcane cultivation.

Nano Carb is a carbon-rich organic soil amendment formulated to enhance soil biological activity and improve the physicochemical properties of agricultural soils [21]. The formulation is designed to enhance soil organic carbon levels, promote the growth and activity of beneficial soil microorganisms, and improve nutrient transformation processes in the rhizosphere [22]. Nano Carb enhances soil biological processes that contribute to improved nutrient availability, root development, and nutrient uptake, thereby supporting overall crop growth beyond its role as a direct nutrient source [23]. The combined effects of Nano Carb on crop performance and soil properties indicate its potential to support sustainable sugarcane production while contributing to the maintenance of soil health.

Considering the need for improved nutrient management and maintenance of soil health in sugarcane production, the present study investigated the response of sugarcane (*Saccharum officinarum* L.) to Nano Carb, a carbon-rich organic soil amendment, under field conditions. The investigation encompassed crop growth and yield attributes, juice quality, plant nutrient uptake, and selected soil health parameters. Changes in soil nutrient availability and soil properties following Nano Carb application were also considered to elucidate its contribution to crop performance and soil fertility management in sugarcane.

Materials and Methods

Experimental site

A field experiment was conducted at Dabhan village, Kheda district, Gujarat, India, to evaluate the effect of Nano Carb on the growth, yield, juice quality, soil health, and nutrient uptake of sugarcane (*Saccharum officinarum* L.) under field conditions.

Experimental design

The experiment was laid out in a Randomized Block Design (RBD) consisting of two treatments with three replications. The treatments comprised Nano Carb applied at 150 kg /acre (T1) and an untreated control (T2). The treatments were randomly allocated within each replication to minimize experimental error.

Microbial composition of the nano carb

Nano Carb is an organic manure developed using ISA Technology and contains the biodecomposer bacterium *Bacillus subtilis* (NCBI GenBank Accession no. QB017572).

Experimental treatments

The field experiment consisted of two treatments. Treatment T1 received a basal soil application of Nano Carb, whereas Treatment T2 was maintained as an untreated control without Nano Carb application. The experiment was conducted in a Randomized Block Design (RBD) with three replications to evaluate the effect of Nano Carb application on sugarcane growth, yield, juice quality, soil health, and nutrient uptake.

Application of nano carb

Nano Carb was applied as a basal soil application at the rate of 150 kg/ acre before planting. The material was uniformly applied in the planting furrows prior to sett placement and thoroughly incorporated into the soil to facilitate its interaction with the developing root system. All other agronomic practices were maintained uniformly across the experimental plots throughout the cropping period.

Recording of growth and yield parameters

Growth and yield parameters were recorded at the respective crop growth stages to assess the effect of Nano Carb application on sugarcane. Bud germination percentage was recorded during the establishment stage, while plant height, number of tillers per clump, number of internodes per cane, cane diameter, and leaf chlorophyll index (SPAD) were measured during the crop growth period. At harvest, yield and yield-contributing parameters were measured, including the number of millable canes per clump, cane length, single cane weight, cane girth, cane volume, and biomass per plant. Cane yield was calculated based on the harvested cane weight and expressed as tonnes per hectare (t/ha).

Juice quality analysis

Juice quality assessment was carried out at harvest using cane samples obtained from each treatment. The parameters analyzed comprised total soluble solids (Brix), sucrose content (Pol), juice purity, Commercial Cane Sugar (CCS), and sugar yield. Sugar yield was calculated using the recorded cane yield and corresponding CCS percentage. Juice purity (%) was calculated as the ratio of sucrose content (Pol, %) to total soluble solids (Brix, %), multiplied by 100. Pol represents the apparent sucrose content of the juice, whereas Brix represents the total soluble solids. Juice purity was calculated using the following formula:

Juice purity (%)=×100

Soil health and nutrient uptake

Post-harvest soil samples were collected from each experimental plot and analyzed for soil organic carbon and microbial population. Microbial counts were expressed as colony-forming units (CFU × 10^6 g/soil). Plant samples collected at harvest were analyzed for nitrogen, phosphorus, and potassium uptake, with nutrient uptake expressed in kg/ha.

Statistical analysis

The recorded data were subjected to analysis of variance (ANOVA) using IBM SPSS Statistics version 26.0. Treatment means were compared using the Least Significant Difference (LSD) test at the 5% probability level ($P \leq 0.05$). Experimental results are presented as mean ± standard error (SE), and statistical significance was determined using the corresponding critical difference (CD) values.

Result and Discussion

Effect of Nano Carb on Bud Germination

Nano Carb application enhanced bud germination in sugarcane compared with the untreated control (Table 1). Germination percentage increased from 84.36% in the untreated control to

94.28% with Nano Carb application, representing an 11.8% increase. The higher germination percentage indicates improved sett establishment during the initial stage of crop growth. The difference between the treatments was statistically significant (CD = 2.89, P ≤ 0.05).

A consistent response was reported in sugarcane under integrated nutrient management involving 75% of the recommended nitrogen through inorganic fertilizer, 25% through farmyard manure, along with *Azotobacter* and *Azospirillum* inoculation. The integrated nutrient management treatment resulted in the highest germination percentage (35.10%), demonstrating improved crop establishment compared with the other nutrient management practices [24].

Treatment	Bud germination (%)
T1- Nano carb	94.28 ± 1.84[a]
T2- Untreated control	84.36 ± 2.06[b]
SEm (±)	0.92 ±
CD (P = 0.05)	2.89
CV (%)	4.21

Table 1: Bud Germination of Sugarcane under Different Treatments.

Effect of nano carb on plant height

Following Nano Carb spraying, plant height increased considerably (Table 2). The treated sugarcane plants grew to an average height of 318.46 cm, compared to 281.84 cm for the untreated control, a 13.0% increase. The higher the plant height, the better the vegetative growth, which is potentially linked to increased nutrient availability and absorption throughout crop development. There was a significant difference between the treatments (CD = 16.50, P < 0.05).

A study on integrated nutrient management in sugarcane reported enhanced vegetative growth with the combined application of recommended dose of fertilizers (RDF), farmyard manure (FYM), phosphate-solubilizing bacteria (PSB), *Azotobacter*, *Acetobacter*, and *Azospirillum*. The treatment recorded a maximum plant height of 190.88 cm at 180 days after planting (DAP), compared with 180.91 cm under the absolute control. The greater plant height was associated with improved nutrient availability resulting from the combined application of organic and microbial nutrient sources, which favoured vegetative growth and plant development [25].

Treatment	Plant height (cm)
T1 - Nano Carb	318.46 ± 10.84[a]
T2 - Untreated control	281.84 ± 9.62[b]
SEm (±)	5.24
CD (P = 0.05)	16.50
CV (%)	4.21

Table 2: Plant Height of Sugarcane under Different Treatments.

Effect of nano carb on tillering

The number of tillers per clump differed markedly between the treatments (Table 3). Nano Carb application promoted tiller production in sugarcane, with the treated plants producing 12.84 tillers per clump compared with 9.86 tillers per clump in the untreated control. The higher tiller production reflects better establishment of productive shoots, which is an important component of the final millable cane population and contributes to overall cane productivity. The treatment resulted in a 30.2% increase in tiller production over the untreated control.

Consistent with the present findings, application of 75% recommended dose of nitrogen (RDN) in combination with two foliar sprays of liquid nano urea enhanced tiller production in sugarcane. Enhanced tillering was associated with greater nitrogen availability and nutrient uptake, supporting vegetative growth and tiller formation. The maximum number of tillers was recorded at 180 DAP/DAR, with 7.40 tillers per hill in the plant crop and 9.07 tillers per hill in the ratoon crop [26].

The observed response is consistent with previous reports on carbon nanofertilizers, which demonstrated improved nutrient absorption and nutrient-use efficiency through controlled nutrient release and enhanced root uptake. Carbon nanomaterials enhanced root development and photosynthetic activity, which were associated with improved vegetative growth and increased crop productivity at optimum application rates [27].

Effect of nano carb on internodes per cane and cane diameter

As shown in Table 4, stem growth characteristics were markedly enhanced by Nano Carb application. The treated plants developed 24.62 internodes per cane, compared with 20.84 internodes in the

Treatment	Tillers/Clump
T1 - Nano Carb	12.84 ± 0.56[a]
T2 -Untreated control	9.86 ± 0.44[b]
SEm (±)	0.27
CD (P = 0.05)	0.85
CV (%)	5.36

Table 3: Tillering Performance of Sugarcane under Different Treatments.

untreated control, representing an increase of 18.1%. Similarly, cane diameter increased from 2.74 cm in the control to 3.14 cm under Nano Carb treatment, reflecting an improvement of 14.6%. The concurrent increase in internode number and cane diameter reflects enhanced cane development and greater accumulation of structural biomass.

In contrast to the results obtained in the present study, nano-fertilizer application produced little variation in stem diameter, with values ranging from 2.48 to 2.52 cm across nano-fertilizer and conventional urea treatments [28].

Treatment	Internodes/ Cane	Cane Diameter (cm)
T1 - Nano Carb	24.62 ± 1.08[a]	3.14 ± 0.12[a]
T2 - Untreated control	20.84 ± 0.94[b]	2.74 ± 0.10[b]
SEm (±)	0.52	0.06
CD (P = 0.05)	1.64	0.19
CV (%)	4.88	4.92

Table 4: Internode Number and Cane Diameter under Different Treatments.

Effect of nano carb on leaf chlorophyll index

Leaf chlorophyll content, expressed as SPAD value, was higher in Nano Carb-treated plants than in the untreated control (Table 5). The chlorophyll index increased from 41.46 SPAD units in the control to 48.62 SPAD units following Nano Carb application, representing a 17.3% increase. The higher SPAD value indicates improved leaf chlorophyll status under Nano Carb treatment, which could be associated with enhanced nutrient availability and improved physiological activity of the plants. Increased chlorophyll content supports efficient light interception and photosynthetic processes, thereby contributing to greater biomass production and crop productivity.

A similar response to nutrient management was observed in another sugarcane study, where the combined application of chemical and organic fertilizers in equal proportions enhanced chlorophyll development. The combined fertilizer treatment recorded the highest chlorophyll index (80.85 SPAD), compared with 71.59 SPAD under chemical fertilizer. The increase in chlorophyll index was associated with improved nitrogen availability under combined fertilization, resulting in a 12.9% increase over the chemical fertilizer control [29].

Treatment	Leaf Chlorophyll Index (SPAD)
T1 - Nano Carb	48.62 ± 1.74[a]
T2 - Untreated control	41.46 ± 1.52[b]
SEm (±)	0.84
CD (P = 0.05)	2.64
CV (%)	4.74

Table 5: Leaf Chlorophyll Index of Sugarcane under Different Treatments.

Effect of nano carb on Millable canes

Nano Carb markedly increased the number of millable canes per clump (Table 6). The treated plants recorded 11.84 millable canes per clump compared with 9.24 in the control. The number of millable canes increased by approximately 28.1%, contributing to the greater cane yield obtained with Nano Carb application.

A comparable response was reported by [30], where the application of 100% N and P + 100% K through bio-methanated distillery effluent (BMDE) resulted in the highest number of millable canes (92.8 × 10^3 canes/ha) in the plant crop, reflecting the positive effect of integrated nutrient management on millable cane production.

Treatment	Millable Canes/Clump
T1 - Nano Carb	11.84 ± 0.52[a]
T2 - Untreated control	9.24 ± 0.46[b]
SEm (±)	0.24
CD (P = 0.05)	0.76
CV (%)	4.84

Table 6: Millable Cane Production under Different Treatments.

Effect of nano carb on cane growth characteristics

Nano Carb treatment notably improved all major cane growth characteristics (Table 7). Cane length increased from 270.84 cm in the untreated control to 302.46 cm under Nano Carb treatment, representing an improvement of approximately 11.7%.

Additionally, the application of Nano Carb substantially increased single cane weight, with T1 recording 1.54 kg/cane compared with 1.22 kg/cane under the untreated control (T2), representing an increase of approximately 26.2%. The higher single cane weight under Nano Carb treatment reflects greater cane biomass accumulation, potentially associated with improved nutrient availability and plant growth under carbon-rich soil amendment conditions.

Comparable results have demonstrated that the combined application of 46 kg N/ha and 15 t compost/ ha, which enhanced cane biomass accumulation through improved nutrient availability, resulted in the highest single cane weight of 1.12 kg in sugarcane, whereas higher nitrogen application rates alone produced comparatively lower cane weights [31].

Nano Carb treatment resulted in greater cane girth and volume than the untreated control. Cane girth was 9.86 cm under Nano Carb treatment, compared with 8.74 cm in the untreated control. Similarly, cane volume increased from 548.36 cm^3 in the untreated control to 694.82 cm^3 with Nano Carb application, representing a 26.7% improvement. Increased cane girth, volume, and single cane weight contributed to greater cane development and higher cane yield under Nano Carb application.

Nano Carb treatment improved the major cane growth parameters compared with the untreated control. As presented in Table 7, cane length increased from 270.84 cm in the untreated control to 302.46 cm with Nano Carb treatment. Similarly, Nano Carb application increased cane girth from 8.74 to 9.86 cm and single cane weight from 1.22 to 1.54 kg, while cane volume increased from 548.36 to 694.82 cm^3. The higher cane girth, single cane weight, and cane volume recorded under Nano Carb application were consistent with improved cane growth observed at harvest.

A comparable response was reported in sugarcane with the application of 75% of the recommended NPK dose (169-84-126 kg/ha) in combination with press mud at 20 t/ha. This treatment produced a cane yield of 119.60 t/ha, compared with 30.41 t/ha for the unfertilized control [32].

Treatment	Cane Length (cm)	Single Cane Weight (kg)	Cane Girth (cm)	Cane Volume (cm^3)
T1 - Nano Carb	302.46 ± 9.84[a]	1.54 ± 0.08[a]	9.86 ± 0.32[a]	694.82 ± 22.46[a]
T2 - Untreated control	270.84 ± 8.62[b]	1.22 ± 0.07[b]	8.74 ± 0.28[b]	548.36 ± 18.82[b]
SEm (±)	4.76	0.04	0.15	10.82
CD (P = 0.05)	14.99	0.13	0.47	34.08
CV (%)	4.96	5.18	4.63	4.82

Table 7: Cane Growth Characteristics under Different Treatments.

Effect of nano carb on biomass production

Application of Nano Carb substantially enhanced biomass accumulation in sugarcane (Table 8). Nano Carb-treated plants produced 18.46 kg biomass per plant compared with 14.82 kg in the untreated control, representing an increase of approximately 24.6%. The greater biomass accumulation was accompanied by improvements in vegetative growth, reflecting enhanced structural growth and biomass accumulation, which ultimately contributed to increased crop productivity.

Comparable results have demonstrated that the combined application of 46 kg N/ha and 15 t compost/ha, which enhanced stalk biomass through improved nutrient availability, produced the highest individual stalk weight of approximately 1.12 kg in sugarcane (*Saccharum officinarum* L.), compared with the individual application of either nutrient source. The integrated nutrient management treatment also resulted in higher cane and sugar yields [33].

Treatment	Biomass/ Plant (kg)
T1 - Nano Carb	18.46 ± 0.72[a]
T2 -Untreated control	14.82 ± 0.64[b]
SEm (±)	0.34
CD (P = 0.05)	1.07
CV (%)	4.71

Table 8: Biomass Production of Sugarcane under Different Treatments

Effect of nano carb on cane yield and juice quality

Nano Carb application resulted in a marked improvement in cane productivity and sugar production (Table 9). The treatment produced the highest cane yield of 112.46 t/ha, compared with 89.82 t/ha under the untreated control, corresponding to a 25.2% increase over the untreated plants. The enhancement in cane productivity was accompanied by a greater improvement in sugar yield, which increased from 10.29 t/ha in the untreated control to 14.43 t/ha with Nano Carb application, representing a 40.2% increase. The greater increase in sugar yield relative to cane yield indicates that Nano Carb application not only promoted higher cane production but also contributed to improved sugar recovery and crop productivity.

In an earlier study on sugarcane, retention of trash mulch supplemented with 250 kg N/ha enhanced crop growth and productivity, resulting in the highest cane yield of 75.4 t/ha in the first ratoon crop [34].

Nano Carb application resulted in marked improvements in the juice quality of sugarcane. Commercial cane sugar (CCS) increased from 11.46% in the untreated control to 12.84% under Nano Carb treatment, indicating greater sugar recovery from the harvested cane. Similarly, total soluble solids (Brix) increased from 19.84% to 21.46%, reflecting a higher concentration of soluble solids in the juice, while sucrose content (Pol) increased from 17.14% to 18.62%, indicating greater sucrose accumulation. Juice purity also improved from 84.26% in the control to 86.74% following Nano Carb application, suggesting a higher proportion of sucrose relative to other soluble constituents in the juice. The simultaneous improvement in Brix, Pol, purity, and CCS indicates that Nano Carb enhanced not only cane productivity but also the quality of juice and the efficiency of sugar recovery.

In another study, the combined application of vermicompost and *Gluconacetobacter diazotrophicus* resulted in the highest commercial cane sugar (CCS) of 9.91 t/ha in the first ratoon crop, compared with 5.44 t/ha in the untreated control. The improvement in CCS was associated with enhanced nutrient availability under integrated nutrient management, which promoted greater sucrose accumulation and sugar recovery [35].

Similar results have been observed in sugarcane, where integrated nutrient management increased cane yield from 58.87 to 73.56 t/ha in the plant crop, representing a 24.95% increase over the control, while the ratoon crop yield increased from 55.25 to 64.12 t/ ha, corresponding to a 16.05% increase. The same study also recorded an increase in sugar yield from 6.90 to 8.75 t/ha in the plant crop and from 6.20 to 7.30 t/ ha in the ratoon crop under integrated nutrient management, revealing improved juice quality and sugar productivity [36].

Treatment	Cane Yield (t/ha)	Commercial Cane Sugar (CCS %)	Juice Brix (%)	Juice Pol (%)	Purity (%)	Sugar Yield (t/ ha)
T1 - Nano Carb	112.46 ± 4.12[a]	12.84 ± 0.42[a]	21.46 ± 0.74[a]	18.62 ± 0.58[a]	86.74 ± 1.46[a]	14.43 ± 0.56[a]
T2 - Untreated control	89.82 ± 3.64[b]	11.46 ± 0.36[b]	19.84 ± 0.62[b]	17.14 ± 0.52[b]	84.26 ± 1.32[b]	10.29 ± 0.48[b]
SEm (±)	2.08	0.21	0.36	0.28	0.72	0.27
CD (P = 0.05)	6.56	0.66	1.13	0.88	2.27	0.85
CV (%)	4.76	4.58	4.41	4.32	4.64	4.71

Table 9: Cane Yield and Juice Quality Attributes under Different Treatments.

Effect of nano carb on soil organic carbon

Nano Carb application greatly improved soil organic carbon content and nutrient uptake in sugarcane compared with the untreated control (Table 8). Soil organic carbon increased from 0.56% in the untreated control to 0.78% following Nano Carb application, suggesting an improvement in soil quality that favoured nutrient availability. This response was reflected in the uptake of major nutrients, with nitrogen uptake increasing from 151.26 to 186.84 kg/ ha and phosphorus uptake from 31.48 to 42.62 kg/ ha as shown in table 10.

Earlier investigations have reported that integrated application of organic and inorganic nutrient sources improves soil organic carbon content. The highest organic carbon content of 0.54% was recorded with 100% bio-methanated distillery effluent (BMDE), compared with 0.43% under RDF (control), while RDF + FYM and RDF + bio-compost (BC) recorded 0.47% and 0.52%, respectively. The increase in soil organic carbon under BMDE application emphasize the beneficial role of organic amendments in enhancing soil carbon accumulation [37].

In another study on sugarcane, organic management recorded the highest total organic carbon content of 23.00 g/ kg in the 0-10 cm soil layer, providing greater soil carbon accumulation and improved soil quality under organic cultivation practices [38].

Treatment	Organic Carbon (%)
T1 - Nano Carb	0.78 ± 0.03^{a}
T2 - Untreated control	0.56 ± 0.02^{b}
SEm (±)	0.01
CD (P = 0.05)	0.03
CV (%)	4.42

Table 10: Soil Organic Carbon Content under Different Treatments.

Effect of nano carb on nutrient uptake

The application of Nano Carb resulted in a noticeable improvement in potassium acquisition, with uptake increasing from 184.36 to 228.74 kg/ha. Enhanced potassium availability may have contributed to improved cane growth through its role in carbohydrate translocation, enzyme activation, and water regulation (Table 11). The simultaneous increase in soil organic carbon and uptake of major nutrients (N, P, and K) illustrate that Nano Carb improved nutrient availability and utilization, thereby promoting better crop growth and productivity. The differences observed for all parameters were statistically significant ($P \leq 0.05$).

The highest nitrogen uptake (226.69 kg /ha) was recorded with press mud application, whereas vermicompost resulted in the maximum phosphorus (41.31 kg/ ha) and potassium (226.52 kg /ha) uptake. In addition, trash incorporation increased nitrogen, phosphorus, and potassium uptake by 5.56%, 5.41%, and 5.01%, respectively, over the control [39].

Treatment	Nitrogen Uptake (kg/ ha)	Phosphorus Uptake (kg/ ha)	Potassium Uptake (kg/ ha)
T1 - Nano Carb	186.84 ± 7.42^{a}	42.62 ± 1.84^{a}	228.74 ± 8.26^{a}
T2 - Untreated control	151.26 ± 6.34^{b}	31.48 ± 1.46^{b}	184.36 ± 7.12^{b}
SEm (±)	3.62	0.92	4.12
CD (P = 0.05)	11.40	2.90	12.97
CV (%)	4.86	4.72	4.58

Table 11: Nitrogen, Phosphorus, and Potassium Uptake under Different Treatments.

Effect of nano carb on soil microbial population

Table 12 demonstrate that Nano Carb application enhanced the soil microbial population compared with the untreated control. The microbial population increased from 5.24×10^{6} CFU/g soil in the control to 8.62×10^{6} CFU/g soil under Nano Carb treatment, showing an increase of approximately 64.5%. The observed increase in microbial population reflects improved microbial activity and favourable soil conditions following Nano Carb application.

Research on sugarcane has recorded the highest soil microbial population (11.19 × 10^{10} CFU/g soil) in sugarcane under residue retention (RR) treatment. The increase in microbial population was attributed to sugarcane residue retention, which supplied readily available organic carbon and other substrates that supported microbial proliferation, enhanced nutrient cycling, and promoted overall soil biological activity [40].

Treatment	Soil Microbial Population (CFU×10^6/g soil)
T1 - Nano Carb	8.62 ± 0.38[a]
T2 - Untreated control	5.24 ± 0.32[b]
SEm (±)	0.18
CD (P = 0.05)	0.57
CV (%)	4.94

Table 12: Soil Microbial Population under Different Treatments.

Conclusion

The present study demonstrates that application of Nano Carb as a carbon-rich organic soil amendment improves sugarcane growth, yield, juice quality, nutrient uptake, and selected soil health parameters under field conditions. Nano Carb application enhanced vegetative development, cane growth attributes, biomass accumulation, and crop productivity, resulting in higher cane and sugar yields compared with the untreated control. Improvements in CCS, Brix, Pol, and juice purity indicate enhanced juice quality and sugar recovery, while increases in soil organic carbon, nutrient uptake, and microbial population reflect favourable changes in soil fertility and biological activity. Nano Carb application can help farmers achieve higher sugarcane production while improving soil health and maintaining soil fertility, thereby supporting more productive and sustainable sugarcane cultivation.

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