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RESEARCH ARTICLE

Effect of natural farming on soil fertility and carbon sequestration: A case study from Eastern India

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Abstract

Soil degradation from excessive chemical inputs threatens agricultural sustainability, particularly in coastal ecosystems of Odisha. This study evaluated the effects of Natural Farming (NF) and Conventional Farming (CF) on soil fertility, carbon sequestration, microbial populations, crop yield and economics in vegetable cultivation (brinjal, okra, tomato) at Krishi Vigyan Kendra (KVK) Jagatsinghpur during rabi 2022-2023. NF involved the use of Jeevamrit, Beejamrit, mulching, Ghanajeevamrit, Neemaster, Bramhastra, Agniastra while CF followed standard recommended practices. Soil samples (0–15 cm) were analyzed before and after harvest for physical, chemical and biological parameters. NF increased soil pH, improved soil organic carbon (SOC) (0.43 % → 0.45 %) and enhanced nitrogen availability (6.46 % increase), while CF showed a slight SOC decline and lower N improvement. SOC stock increased by 0.16–0.62 Mg/ha under NF but declined by 0.25 to 2.49 Mg/ha under CF. NF significantly increased bacterial (47.5 %), fungal (40.12 %) and actinomycetes (70.4 %) populations over CF. Crop yields under NF were marginally lower, but reduced cultivation costs led to slightly higher benefit-cost ratios (B:C) in all crops. Correlation analysis revealed significant interrelations among soil properties, with carbon sequestration negatively correlated with pH (r = -0.85*). The results demonstrate NF's potential to improve soil health, enhance carbon sequestration and maintain profitability in coastal vegetable systems, supporting its promotion as a sustainable alternative to CF in climatic vulnerable coastal areas in Odisha and similar agro-climatic regions of the country and beyond.

Keywords: carbon sequestration; conventional farming; crop yield and economics; microbial populations; natural farming

Introduction

Soil fertility is critical for sustaining agricultural productivity, ensuring food security and supporting millions of farmers in India. The country's heavy reliance on agriculture necessitates fertile soils for crop production and the long-term viability of farming systems. However, India faces significant soil degradation challenges, primarily due to excessive chemical fertilizer use, mono-cropping and poor crop management practices, which threaten agricultural sustainability (1). Approximately 50–60 % of Indian soils are deficient in one or more essential nutrients, with nitrogen, phosphorus and potassium being the most common deficiencies. Soil degradation in India is further exacerbated by declining soil organic carbon (SOC), widespread soil erosion, acidification and salinity issues, particularly in coastal ecosystems where high fertilizer use is prevalent due to intensive cultivation systems. This problem is acute in states like Odisha, where rice-dominated systems and soil erosion have severely impacted soil quality (2).

The overuse of chemical fertilizers and pesticides disrupts soil microbial activity, reduces nutrient cycling and leaves harmful residues, further degrading soil health and biodiversity (3). These practices not only harm soil fertility but also contribute to greenhouse gas emissions, making carbon sequestration a critical aspect of mitigating climate change (4). Carbon sequestration, which refers to the process of capturing atmospheric carbon dioxide and storing it in the soil, is essential for improving soil organic matter and overall soil health. However, the declining Nitrogen-Use-Efficiency (NUE) in chemical fertilizer-dominated systems, coupled with the deterioration of SOC, has hindered the long-term sustainability of agricultural practices (5).

India's journey to food self-sufficiency since the Green Revolution has been achieved at the cost of soil degradation and ecological imbalance. The intensive use of NPK fertilizers and selection of high-yielding crop varieties have not only reduced soil quality but also increased the vulnerability of agro-ecosystems to climate extremes. Coastal ecosystems face heightened risks due to the high use of fertilizers for crops like vegetables, which demand greater nutrient inputs. In these lowland areas, chemical runoff significantly affects soil, water and surrounding ecosystems. In the

specific context of coastal Odisha, studies have quantified high soil erosion rates and sediment yield, highlighting the vulnerability of these landscapes (1, 2). Furthermore, the quantitative status of soil organic carbon in the region is often low, a key indicator of degradation that justifies the need for restorative practices like natural farming in this location (6). Addressing these challenges requires a shift towards natural farming practices that promote ecological balance and soil health while reducing dependency on external inputs.

Natural farming, model advocates cultivation practices that rely on locally available resources, promoting a circular economy that minimizes waste (7). The principles of natural farming are deeply rooted in India's ancient agricultural practices, which emphasized harmony with nature and the sustainable use of resources. Traditional methods like crop rotation, use of organic manures and integration of livestock in farming systems reflect the agro-ecological wisdom of Indian civilization. These methods have been integral to Indian culture and were practiced extensively before the advent of industrialized farming. The benefits of natural farming extend beyond cost reduction, as it enhances soil health, supports carbon sequestration and improves biodiversity, all while reducing the environmental impact of agriculture. Practices such as mulching, incorporating crop residues and microbial activators improve SOC levels, leading to better nutrient availability and crop productivity.

Despite its potential, the holistic effects of natural farming on soil health, carbon sequestration and crop yields remain underexplored, particularly in unique agro-ecosystems like the coastal plains. While individual studies have highlighted the benefits of natural farming practices, comprehensive research evaluating their long-term impact on soil fertility and carbon dynamics in diverse agro-climatic zones is lacking (8). Coastal regions, with their unique lowland conditions and high fertilizer usage, are particularly understudied, especially concerning high-input crops like vegetables. Such studies are essential to develop sustainable strategies tailored to these vulnerable ecosystems. This study was conducted at Krishi Vigyan Kendra (KVK) Jagatsinghpur, a coastal district of Odisha, located approximately 30 km from the Bay of Bengal to evaluate the effects of natural farming practices on soil fertility, carbon sequestration in vegetable cultivation, thereby providing much-needed empirical data for this region.

Materials and Methods

Site description

The study was carried out at the Experimental Farms of KVK Jagatsinghpur, Odisha, as shown in Fig. 1. The district is situated in East and Southeast Coastal Plain Agro Climatic Zone of Odisha and total geographical area of district is 1668 sq km.

Experimental design and crop management

The study employed a comparative field experiment involving two types of farmings: Natural Farming (NF) and Conventional Farming (CF). Vegetables crop like brinjal (cv. Utkal Anushree), okra (cv. Madhuri) and tomato (cv. Utkal Raja) were grown during rabi 2022 and 2023. The brinjal, okra and tomato seedlings raised under different farming systems were transplanted on 12th December in 2022 and 3rd December in 2023 at spacing of 75 cm × 60 cm for brinjal, 60 cm × 30 cm for okra and 90 cm × 60 cm for tomato in plots of 4 m × 3 m. Sole vegetable crops (tomato, okra, brinjal) were cultivated under CF and NF system. Straw mulch was also applied under NF system. The NF system was implemented as per the established protocol (9). The seeds were treated with Beejamrit @ 20 mL/20 g, one day before sowing and kept overnight for drying. The nursery bed was applied with the Ghanajeevamrit @ 100 g/m^2. The Jeevamrit was sprinkled on the nursery bed @ 10 %, one day

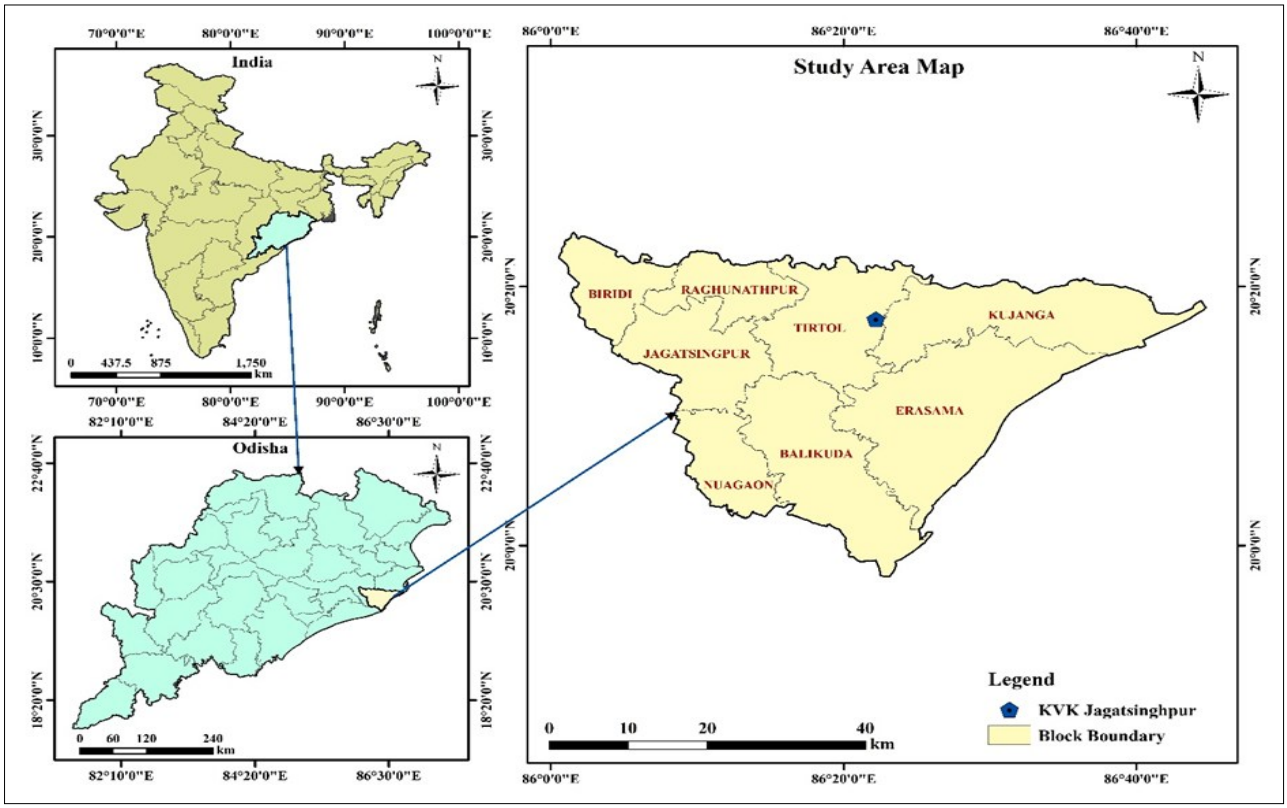


Fig. 1. Location of the study area (Generated by ArcGIS software Version: 10.8.1, developed by ESRI).

before uprooting the seedlings. The roots of uprooted seedlings were dipped in Jeevamrit for 2–3 min before transplanting. Ghanajeevamrit @ 5 q/ha was mixed in plots at the time of field preparation and Jeevamrit was applied through foliar application at 15 days interval in the standing crop. For the management of insect-pests, Neemaster @ 500 L/ha, Bramhastra @ 3 % and Agniastra @ 3 % were used alternatively, at fortnightly interval starting from one week after transplanting till one week before harvest. Under CF crop was grown following standard package of practices followed by the farmers.

Soil sampling and analysis

To study the effect of NF vs CF, representative soil samples (0–15 cm depth) were collected with seven replications before and after the harvest of crop to determine the soil physical and biological properties. The prepared samples were analyzed for using standard analytical methods. Soil pH was estimated by Jackson method (10). Available nitrogen was determined following Subbiah and Asija method (11). Available phosphorus and potassium were determined using Bray and Kurtz method (12). Soil organic carbon was determined by the Walkley and Black method (13). Bulk density was determined from samples collected using core samplers. SOC stock was calculated using Eqn. 1.

$$\text{SOC stock (Mg ha}^{-1}) = [\text{SOC (g g}^{-1}) \times \text{BD (Mg m}^{-3}) \times \text{area (ha)} \times \text{soil depth (m)}] \quad \text{(Eqn. 1)}$$

Carbon sequestration was determined taking the difference of SOC stock before and after the sowing of the crop, as shown in Eqn. 2.

$$C_{sequestered}\ (\text{Mg C ha}^{-1}\ \text{soil}) = SOC_{final} - SOC_{initial.} \quad \text{(Eqn. 2)}$$

Where, $SOC_{initial}$ and SOC_{final} indicated the SOC stocks before sowing and after harvesting of the crops. Positive and negative value indicates the SOC gains and losses, respectively for the cropping system. Soil bacteria and fungi were enumerated using a standard technique.

Data analysis

Crop yield was recorded at the end of the season from each experimental plot. The data on various parameters generated during the study was statistically analysed for significance tests at 5 % probability level ($p = 0.05$) using R software.

Initial soil characteristics of the experimental site

The initial soil properties of the experimental field (Table 1) indicate that the soil has a bulk density of 1.48 Mg m^{-3}, reflecting a moderately compacted profile typical of cultivated rainfed soils. The soil reaction is slightly acidic with a pH of 5.78, while the electrical conductivity (0.49 dS m^{-1}) confirms non-saline conditions. The organic carbon content (0.42 %) is low, suggesting limited organic matter accumulation. Among the available nutrients, nitrogen (215.33 kg ha^{-1}) is in the moderate range, whereas phosphorus (14.29 kg ha^{-1}) is low and potassium (125.67 kg ha^{-1}) falls within the medium range for the region. The microbial profile demonstrates a functionally active soil microbiome, dominated by bacteria (4.78×10^7 CFU g^{-1}), followed by fungi (5.23×10^5 CFU g^{-1}) and actinomycetes (0.49×10^5 CFU g^{-1}), indicating a balanced microbial consortium supportive of soil biological processes.

Table 1. Soil testing parameters of the experimental site

Soil parameters	Soil data
Bulk density (Mg/m^3)	1.48
pH	5.78
EC (dS.m^{-1})	0.49
Soil Organic Carbon (%)	0.42
Nitrogen (kg/ha)	215.33
Phosphorus (kg/ha)	14.29
Potassium (kg/ha)	125.67
Soil Bacteria (CFU×10^7/g of soil)	4.78
Soil fungi (CFU ×10^5/g of soil)	5.23
Soil actinomycetes (CFU ×10^5/g of soil)	0.49

Results and Discussion

Comparison of key soil health parameters between NF and CF practices before sowing and after harvesting during the year 2022 and 2023, is shown in Fig. 2 using boxplot analysis.

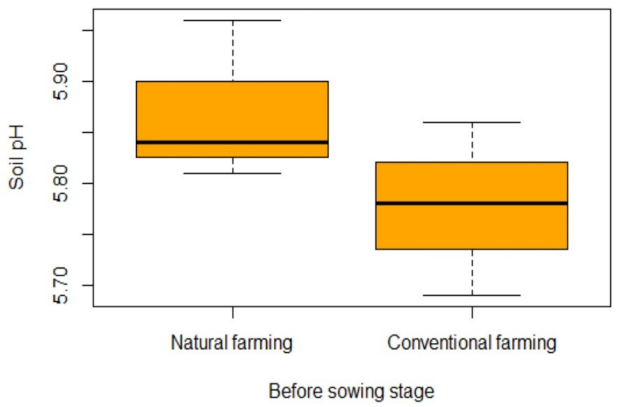
Soil nutrient dynamics

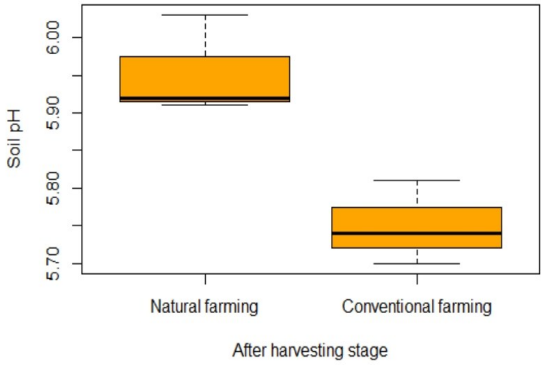
During 2022 and 2023, the soil reaction remained slightly acidic in both systems. The pH under the NF system increased from 5.91 to 5.98, whereas under the CF system, the pH showed a slight increase from 5.82 to 5.83 (Fig. 1). This indicates that natural farming practices contribute to better pH stabilization compared to conventional methods. SOC levels increased after the intervention. Under NF, SOC improved from 0.43 % to 0.45 %, while in CF, it declined slightly from 0.44 % to 0.42 %. This net gain in SOC under NF can be attributed to the constant input of organic matter through mulching and liquid amendments like Jeevamrit, which serve as a substrate for soil microbes, leading to the formation of stable humus (14). In contrast, CF systems often lead to a priming effect, where fresh organic matter inputs are low and existing SOC is mineralized at a faster rate due to tillage and lack of protective organic cover (14).

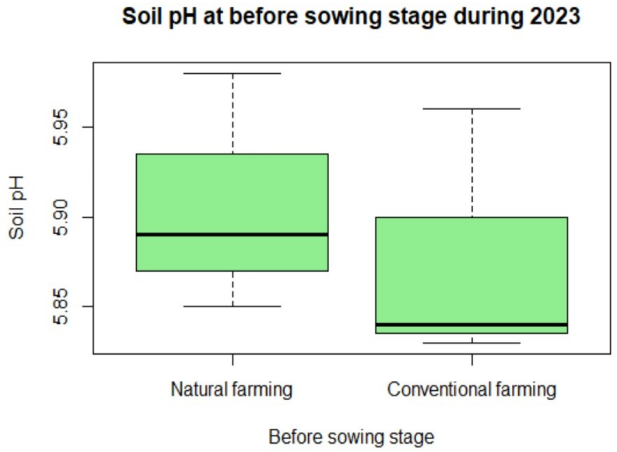
Nitrogen (N) availability increased from 218.42 mg/kg to 232.50 mg/kg in NF, reflecting a 6.46 % increase, while under CF, nitrogen increased from 222.25 mg/kg to 228.92 mg/kg, a 3.00 % rise. The more pronounced effect in NF is likely due to the gradual mineralization of nitrogen from the diverse organic inputs (e.g. Jeevamrit, mulch), which synchronizes nutrient release with plant uptake. This biological mineralization process, driven by the enhanced microbial community, provides a more sustained nitrogen supply compared to the rapid, often leachable, influx from synthetic fertilizers in CF (15).

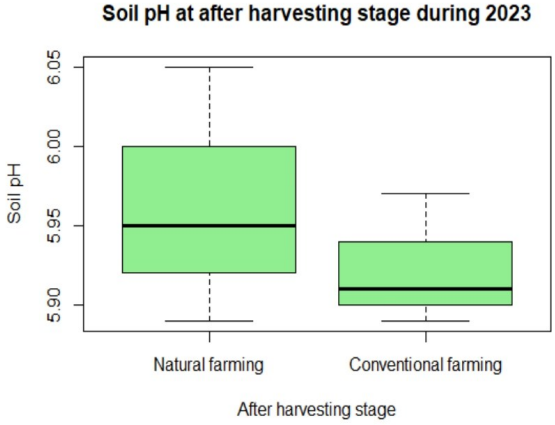
Phosphorus (P) content increased from 16.58 mg/kg to 18.79 mg/kg in natural farming (13.31 % increase) and from 16.93 mg/kg to 19.30 mg/kg in CF (14.00 % increase). The slightly higher immediate increase in CF is due to the quick release of phosphorus from synthetic fertilizers, whereas in NF, the improved microbial activity helped in phosphorus solubilization. Microbes, particularly phosphate-solubilizing bacteria and mycorrhizal fungi, play a crucial role in mobilizing insoluble phosphorus pools in the soil, a process that is stimulated by the carbon-rich environment of NF systems, ensuring long-term P availability (16).

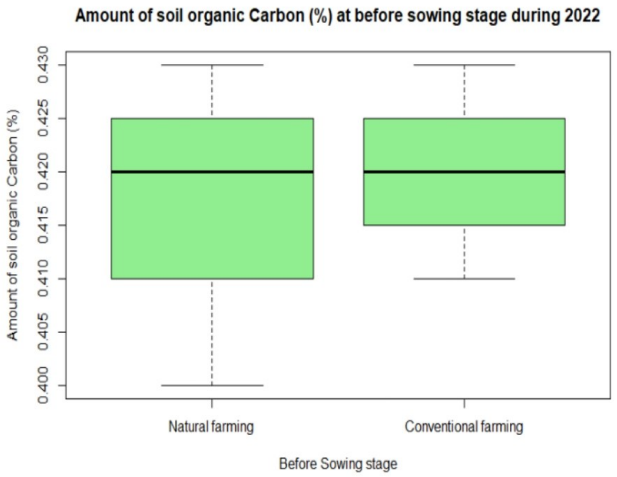
Potassium (K) levels decreased in the NF plots from 140.42 mg/kg to 135.92 mg/kg (a 3.2 % drop), while the CF plots increased from 132.25 mg/kg to 140.42 mg/kg (a 6.18 % rise). The decline in NF may be because crops used more potassium and in CF the increase likely came from the quick release of chemical fertilizers. In NF, potassium is released slowly from crop residues and through microbial processes and in sandy coastal soils it can also leach easily.

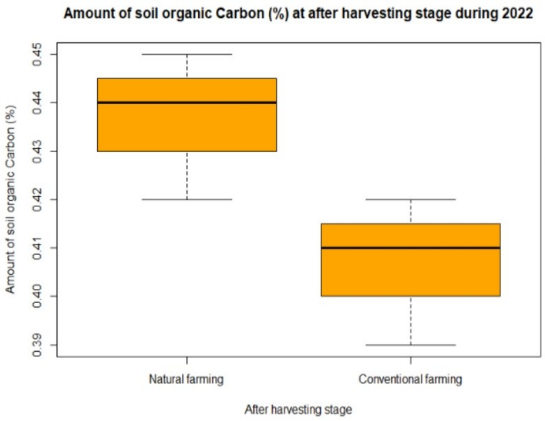

Soil pH at before sowing stage during 2022
Soil pH
5.70
5.80
5.90
Natural farming
Conventional farming
Before sowing stage

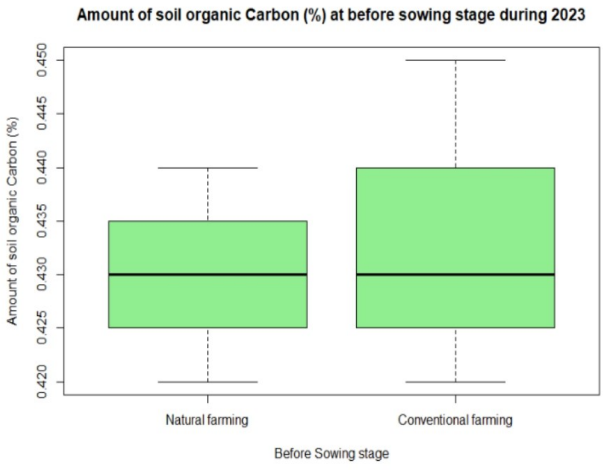

Soil pH at after harvesting stage during 2022
Soil pH
5.70
5.80
5.90
6.00
Natural farming
Conventional farming
After harvesting stage

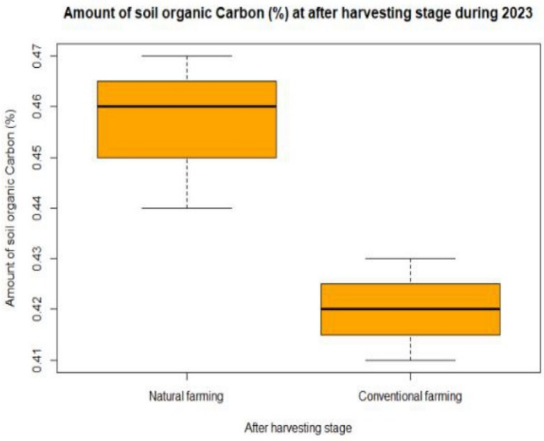

Soil pH at before sowing stage during 2023
Soil pH
5.85
5.90
5.95
Natural farming
Conventional farming
Before sowing stage

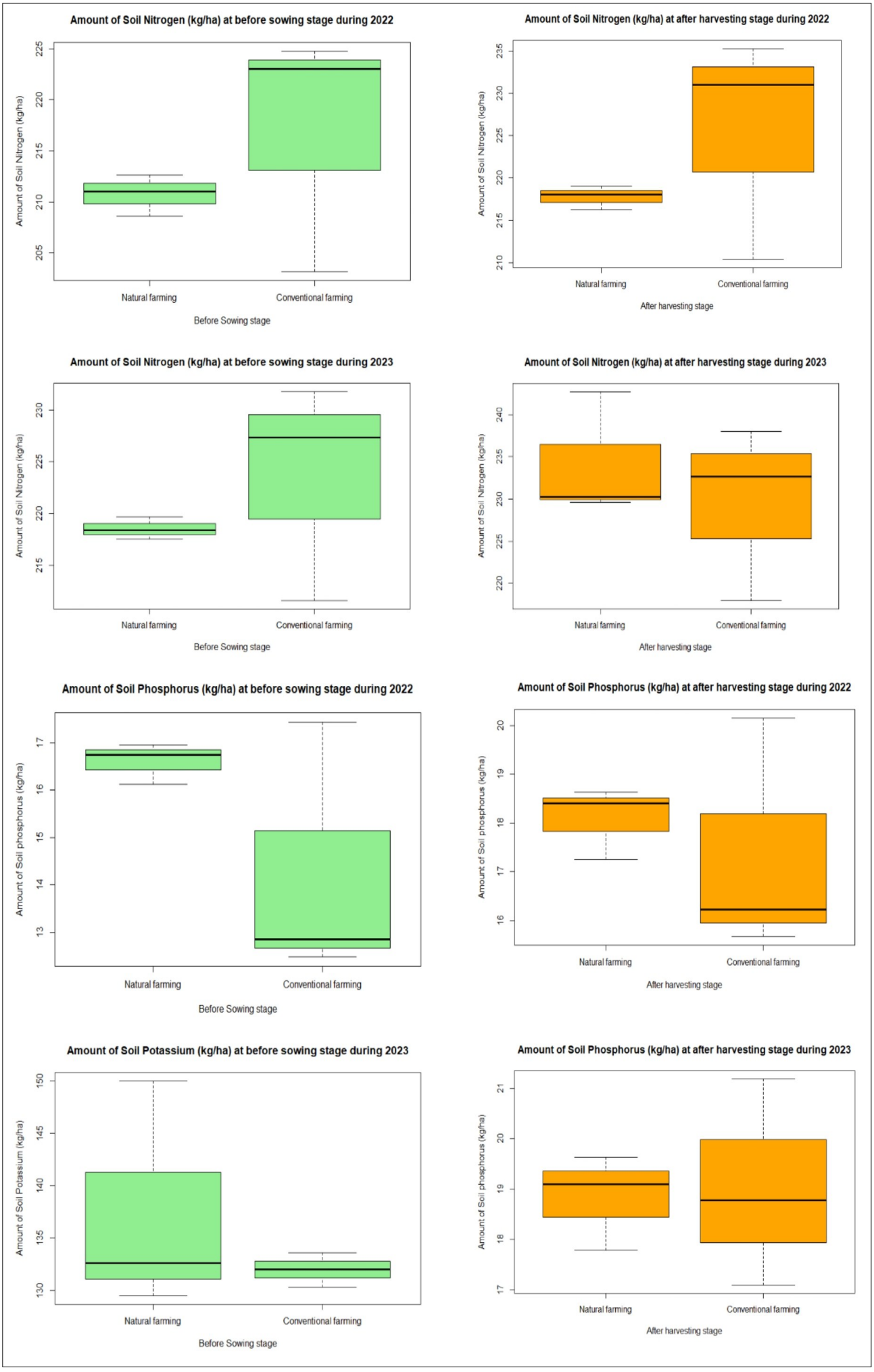

Soil pH at after harvesting stage during 2023
Soil pH
5.90
5.95
6.00
6.05
Natural farming
Conventional farming
After harvesting stage

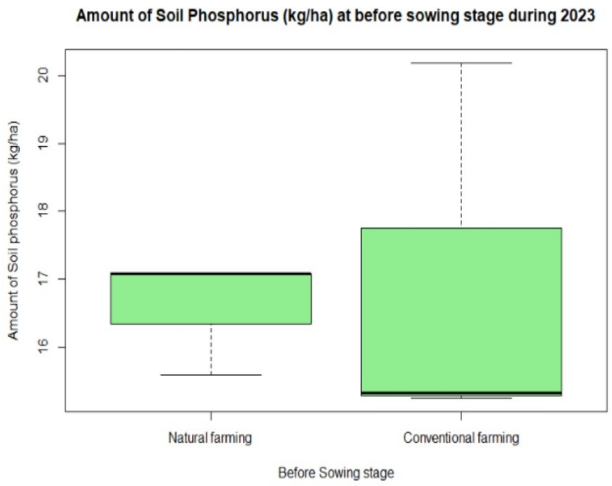

Amount of soil organic Carbon (%) at before sowing stage during 2022
Amount of soil organic Carbon (%)
0.400
0.405
0.410
0.415
0.420
0.425
0.430
Natural farming
Conventional farming
Before Sowing stage

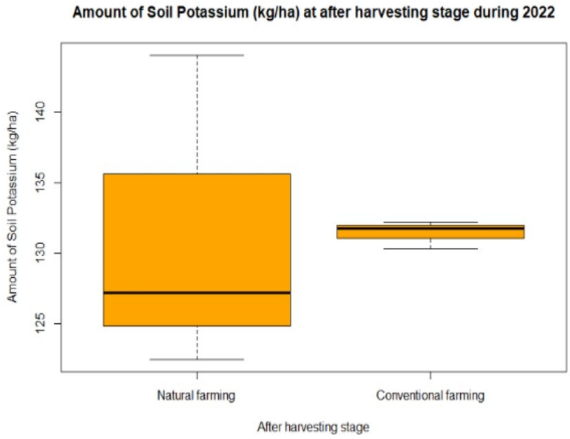

Amount of soil organic Carbon (%) at after harvesting stage during 2022
Amount of soil organic Carbon (%)
0.39
0.40
0.41
0.42
0.43
0.44
0.45
Natural farming
Conventional farming
After harvesting stage

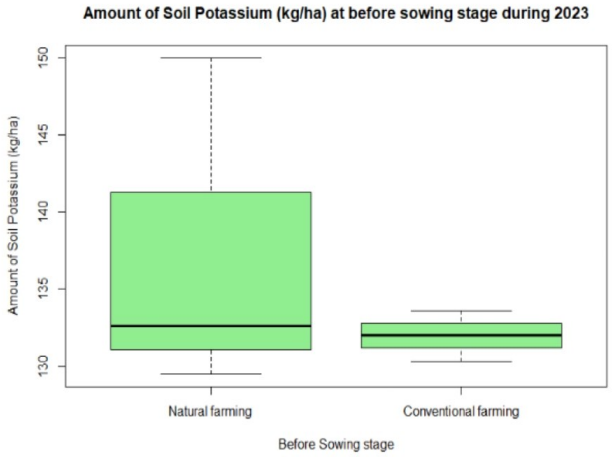

Amount of soil organic Carbon (%) at before sowing stage during 2023
Amount of soil organic Carbon (%)
0.420
0.425
0.430
0.435
0.440
0.445
0.450
Natural farming
Conventional farming
Before Sowing stage

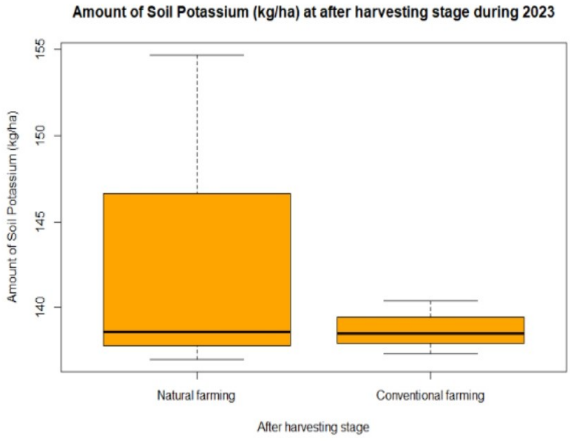

Amount of soil organic Carbon (%) at after harvesting stage during 2023
Amount of soil organic Carbon (%)
0.41
0.42
0.43
0.44
0.45
0.46
0.47
Natural farming
Conventional farming
After harvesting stage

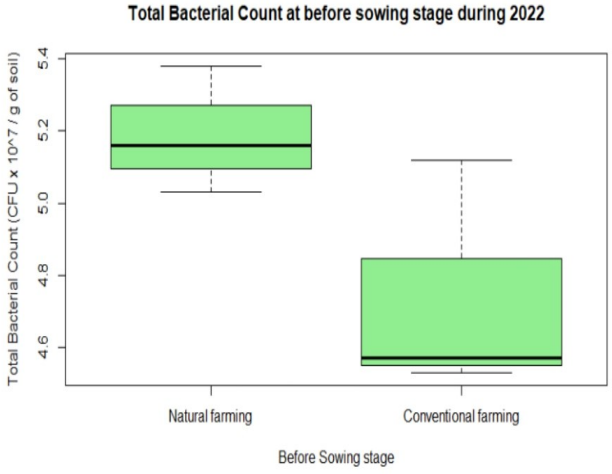

Amount of Soil Nitrogen (kg/ha) at before sowing stage during 2022
Amount of Soil Nitrogen (kg/ha)
Natural farming
Conventional farming
Before Sowing stage
Amount of Soil Nitrogen (kg/ha) at after harvesting stage during 2022
Amount of Soil Nitrogen (kg/ha)
Natural farming
Conventional farming
After harvesting stage
Amount of Soil Nitrogen (kg/ha) at before sowing stage during 2023
Amount of Soil Nitrogen (kg/ha)
Natural farming
Conventional farming
Before Sowing stage
Amount of Soil Nitrogen (kg/ha) at after harvesting stage during 2023
Amount of Soil Nitrogen (kg/ha)
Natural farming
Conventional farming
After harvesting stage
Amount of Soil Phosphorus (kg/ha) at before sowing stage during 2022
Amount of Soil phosphorus (kg/ha)
Natural farming
Conventional farming
Before Sowing stage
Amount of Soil Phosphorus (kg/ha) at after harvesting stage during 2022
Amount of Soil phosphorus (kg/ha)
Natural farming
Conventional farming
After harvesting stage
Amount of Soil Potassium (kg/ha) at before sowing stage during 2023
Amount of Soil Potassium (kg/ha)
Natural farming
Conventional farming
Before Sowing stage
Amount of Soil Phosphorus (kg/ha) at after harvesting stage during 2023
Amount of Soil phosphorus (kg/ha)
Natural farming
Conventional farming
After harvesting stage

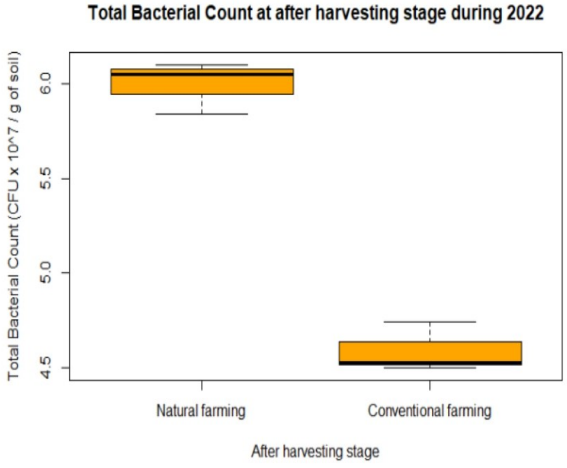

Amount of Soil Phosphorus (kg/ha) at before sowing stage during 2023
Amount of Soil phosphorus (kg/ha)
16
17
18
19
20
Natural farming
Conventional farming
Before Sowing stage

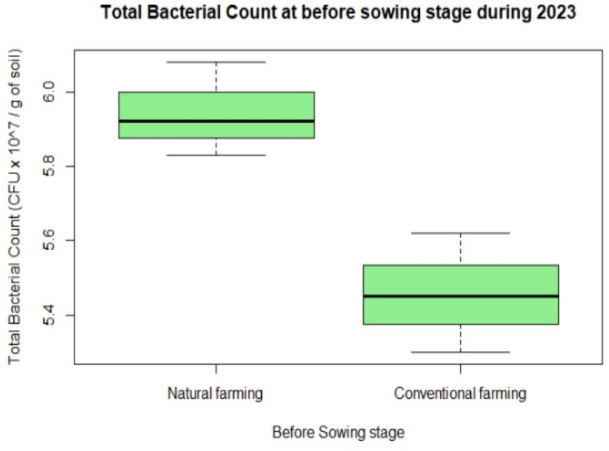

Amount of Soil Potassium (kg/ha) at after harvesting stage during 2022
Amount of Soil Potassium (kg/ha)
125
130
135
140
Natural farming
Conventional farming
After harvesting stage

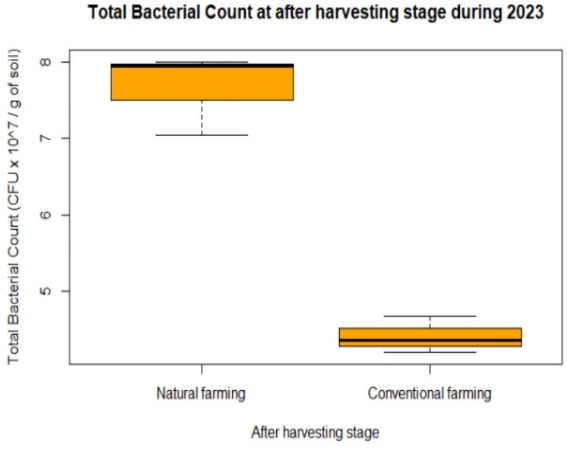

Amount of Soil Potassium (kg/ha) at before sowing stage during 2023
Amount of Soil Potassium (kg/ha)
130
135
140
145
150
Natural farming
Conventional farming
Before Sowing stage


Amount of Soil Potassium (kg/ha) at after harvesting stage during 2023
Amount of Soil Potassium (kg/ha)
140
145
150
155
Natural farming
Conventional farming
After harvesting stage


Total Bacterial Count at before sowing stage during 2022
Total Bacterial Count (CFU x 10^7 / g of soil)
4.6
4.8
5.0
5.2
5.4
Natural farming
Conventional farming
Before Sowing stage


Total Bacterial Count at after harvesting stage during 2022
Total Bacterial Count (CFU x 10^7 / g of soil)
4.5
5.0
5.5
6.0
Natural farming
Conventional farming
After harvesting stage


Total Bacterial Count at before sowing stage during 2023
Total Bacterial Count (CFU x 10^7 / g of soil)
5.4
5.6
5.8
6.0
Natural farming
Conventional farming
Before Sowing stage


Total Bacterial Count at after harvesting stage during 2023
Total Bacterial Count (CFU x 10^7 / g of soil)
5
6
7
8
Natural farming
Conventional farming
After harvesting stage

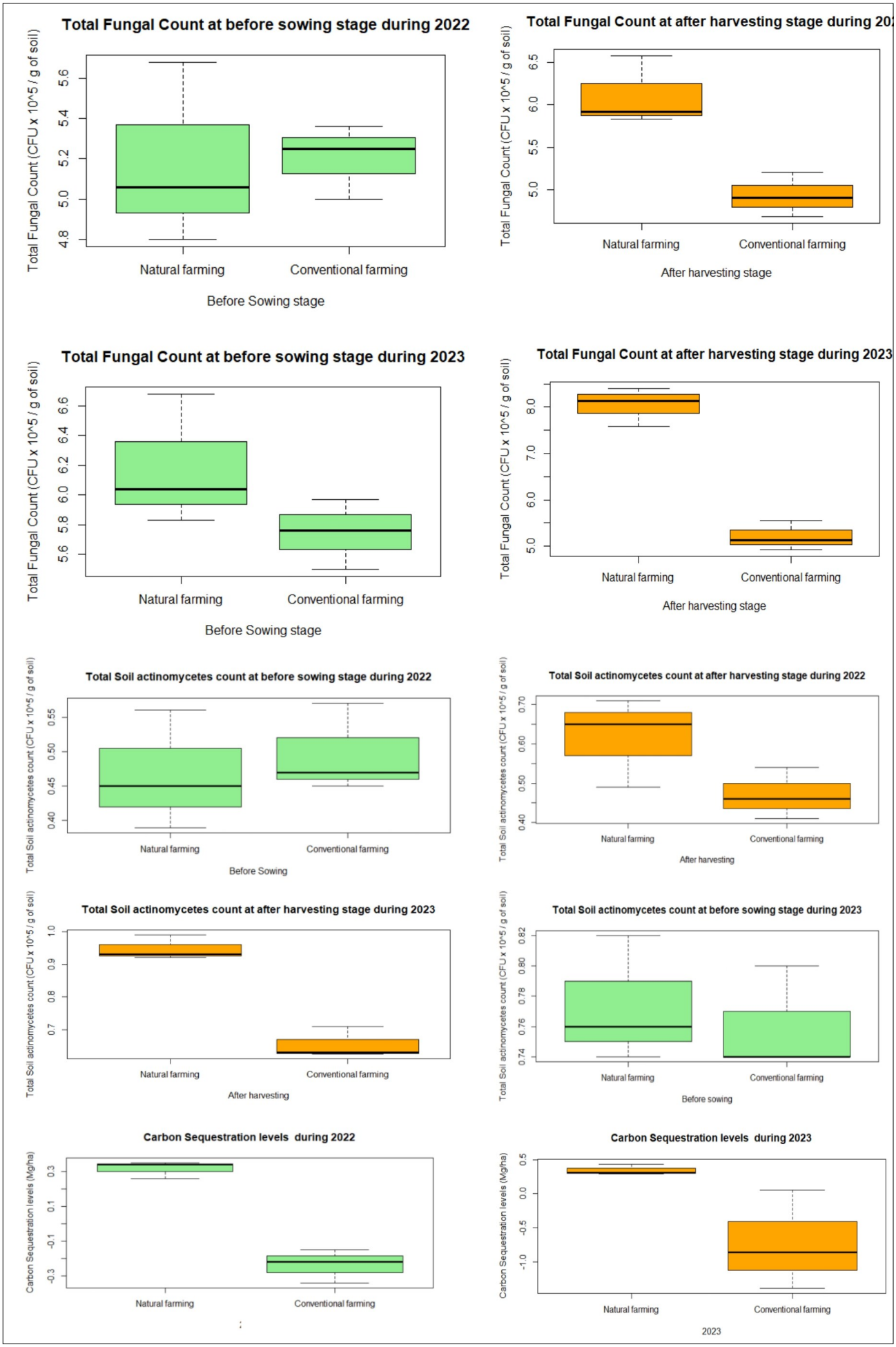


Fig. 2. Comparison of key soil health parameters between natural farming and conventional farming practices before sowing and after harvesting during 2022 and 2023, using boxplot analysis.

Higher microbial activity in NF may temporarily hold potassium within microbial biomass. Even though NF shows a short-term decline, it generally helps retain potassium better in the long run and reduces nutrient loss compared to chemical fertilizers (17).

Carbon sequestration

Under NF, SOC consistently increased, with gains ranging from 0.16 to 0.62 Mg/ha and the average SOC rising from 9.42 to 9.76 Mg/ha, indicating improved carbon sequestration. This increase is mainly due to core NF practices: mulching reduces erosion and temperature fluctuations, slowing SOC decomposition, while bio-enhancers like Jeevamrit introduce beneficial microorganisms that help convert fresh organic matter into stable carbon forms (18, 19). In contrast, CF shows SOC losses of 0.25 to 2.49 Mg/ha, with the average stock declining from 10.24 to 9.43 Mg/ha, largely because intensive tillage speeds up carbon oxidation and organic matter inputs are low (4). These results align with earlier findings from India, which demonstrate a faster improvement in SOC under NF than under conventional practices (6, 20).

Soil microbial population

During 2022, the average soil bacterial count increased from 5.2×10^7 cfu/g soil to 5.98×10^7 cfu/g soil under NF, showing a 14.9 % increase. This improvement can be attributed to the enhanced microbial environment created by organic inputs, such as Jeevamrit, farmyard manure and mulching, which provide a favorable habitat and nutrients for bacterial proliferation. In contrast, in the CF system, the bacterial count declined from 4.78×10^7 cfu/g soil to 4.61×10^7 cfu/g soil, showing a 3.56 % reduction. The decline in CF is likely due to the repeated use of chemical fertilizers and pesticides, which suppress beneficial microbial populations and reduce soil biological activity. During 2023, the bacterial count further increased in NF, rising from 5.95×10^7 cfu/g soil to 7.67×10^7 cfu/g soil, reflecting a 28.91 % increase. The continued rise suggests an accumulation of organic matter and improved soil microbial habitat due to reduced chemical disturbances and increased root exudates. Conversely, the bacterial count in CF declined from 4.53×10^7 cfu/g soil to 4.47×10^7 cfu/g soil, marking a 1.2 % reduction. This significant drop indicates long-term microbial stress due to synthetic inputs, reduced organic matter availability and lower microbial resilience. After two cropping seasons, the bacterial count under NF increased by 47.5 % compared to the initial field conditions, while CF showed a decline. This remarkable increase in NF is driven by the enhanced microbial environment created by organic inputs, which provide a favorable habitat and continuous food source for bacterial proliferation. In contrast, the decline in CF is likely due to the suppressive effect of repeated chemical fertilizer and pesticide use on beneficial microbial populations (21).

The fungal count was also significantly influenced by different farming systems during both the seasons (Fig. 1). The fungal count under NF was statistically higher than CF. During 2022, the average soil fungal count increased from 6.12×10^5 cfu/g soil to 7.02×10^5 cfu/g soil under NF, showing a 6.96 % increase. During 2023, the fungal count further increased in NF, rising from 6.12×10^5 cfu/g soil to 7.02×105 cfu/g soil, reflecting a 14.7 % increase. After two years of study, the fungal count under NF is 7.02×10^5 cfu/g soil which was significantly higher than that under CF. Similarly, the population of soil fungi (7.02×10^5 cfu/g soil) under NF increased by 40.12 % over CF. The proliferation of fungi is critical for soil aggregation and the decomposition of complex organic compounds like cellulose and lignin present in mulch, which is a key component of NF (22).

The population of actinomycetes in the soil after harvest of crop was significantly different under different systems (Fig. 1). The increase in actinomycetes population followed the similar trend as that of fungi population. During 2022, actinomycetes population increased from 0.51×10^5 cfu/g soil to 0.60×10^5 cfu/g soil in NF system and reduced from 0.49×10^5 cfu/g soil to 0.47×10^5 cfu/g soil under CF. In the year 2023, actinomycetes population increased from 0.78×10^5 cfu/g soil to 0.87×10^5 cfu/g soil and reduced from 0.76×10^5 cfu/g soil to 0.58×10^5 cfu/g soil in NF and CF, respectively. The actinomycetes population under NF was significantly higher than that under CF. After two years of study, the actinomycetes population under NF (0.87×10^5cfu/g soil) increased by 70.4 % in comparison to CF. Actinomycetes are vital for breaking down tough organic matter and producing antibiotics, contributing to overall soil health and disease suppression (23). The overall enrichment of microbial life under NF creates a resilient and self-sustaining soil ecosystem, crucial for long-term nutrient cycling and soil structure maintenance (24).

Crop yield and cost economics

The comparative analysis of crop yield and cost economics between CF and NF revealed that the cost of cultivation was consistently lower under NF across all crops studied, as presented under Table 2. For brinjal, the cultivation cost in NF (Rs 96500/ha) was about 12.4 % less than in CF (₹110200/ha), while yields were slightly lower in NF (207 q/ha) compared to CF (232 q/ha). A similar trend was observed in okra, where NF reduced the cultivation cost by approximately 13.3 % (₹66400/ha vs ₹76600/ha) with a modest reduction in yield (102 q/ha vs 116 q/ha). In tomato, the cultivation cost was reduced by nearly 14 % under NF (₹74000/ha) relative to CF (₹86100/ha), accompanied by a yield reduction from 217 q/ha to 178 q/ha. Despite the lower yields, the benefit–cost (B:C) ratio was marginally higher in NF across all crops, indicating improved economic efficiency. Specifically, the B:C ratio increased from 2.11 to 2.15 in brinjal, 2.28 to 2.32 in okra and 2.83 to 2.92 in tomato, suggesting that NF, with its lower input costs, can offer competitive or superior profitability compared to CF.

The slightly lower yields under NF are common during the shift from CF because the soil needs time to rebuild its biology and improve nutrient cycling (25). However, the substantial reduction in input costs under NF enhances farmers' profits and improves the BC ratio. It also lowers financial risk, contributing to greater stability for farming households (26). The yield outcomes under NF are consistent with findings from other studies on organic nutrient management in similar crops (27). The positive effect of Jeevamrit on crop growth and yield is also reported in several studies (9).

Table 2. Effect of CF and NF on crop yield and cost economics

Crop Name	Cost of cultivation (Rs. /ha)		Yield (Q/ha)		B: C Ratio	
	CF	NF	CF	NF	CF	NF
Brinjal	110200	96500	232	207	2.11	2.15
Okra	76600	66400	116	102	2.28	2.32
Tomato	86100	74000	217	178	2.83	2.92

Correlation among various parameters

Correlation analysis showed clear links among the soil properties (Fig. 3, Table 3). Carbon sequestration had a strong negative correlation with soil pH (r = –0.85). This means that the slightly acidic soils in this area support better carbon retention because processes like organic matter binding with aluminium and iron oxides work more actively at lower pH (27). All soil biological parameters, such as bacteria, fungi and actinomycetes, showed strong positive correlations with each other ($p < 0.001$). This shows that the soil microbial groups depend on each other. Soil organic carbon had a positive correlation with nitrogen (r = 0.95*) and with bacterial count (r = 0.85**). This highlights the close relationship between organic matter, nutrient supply and an active microbial population in improving soil health (28).

Conclusion

The two-year field study clearly establishes the superiority of NF over CF in improving soil health, enhancing carbon sequestration and ensuring economic viability in coastal vegetable production systems in Odisha. NF improved soil organic carbon (SOC) content by 4.65 % (0.43 % → 0.45 %), whereas CF caused a 4.55 % decline (0.44 % → 0.42 %). SOC stock gains under NF ranged from 0.16 to 0.62 Mg C ha^{-1}, while CF suffered losses of 0.25 to 2.49 Mg C ha^{-1}, demonstrating NF's significant role as a carbon sink. Nitrogen availability increased by 6.46 % under NF compared to 3.00 % under CF, demonstrating the sustained nutrient release potential of organic inputs. Soil microbial activity showed remarkable improvement under NF, with bacterial, fungal and actinomycetes populations increasing by 47.5 %, 40.12 % and 70.4 %

Table 3. Correlation matrix of key soil health parameters under natural farming practices

Parameter	CS	pH	SOC	N	P	K	BC	FC	AC
CS	1								
pH	-0.85*	1							
SOC	0.92**	-0.78*	1						
N	0.88**	-0.81*	0.95**	1					
P	0.65	-0.55	0.71	0.68	1				
K	0.21	-0.15	0.30	0.25	0.48	1			
BC	0.79*	-0.70	0.85**	0.82**	0.60	0.18	1		
FC	0.52	-0.45	0.61	0.58	0.40	0.10	0.87**	1	
AC	0.50	-0.43	0.59	0.56	0.38	0.09	0.84**	0.95**	1

*CS: Carbon Sequestration; SOC: Soil Organic Carbon; N: Nitrogen; P: Phosphorus; K: Potassium; BC: Bacterial Count; FC: Fungal Count; AC: Actinomycetes Count. *$p < 0.05$, *$p < 0.01$.

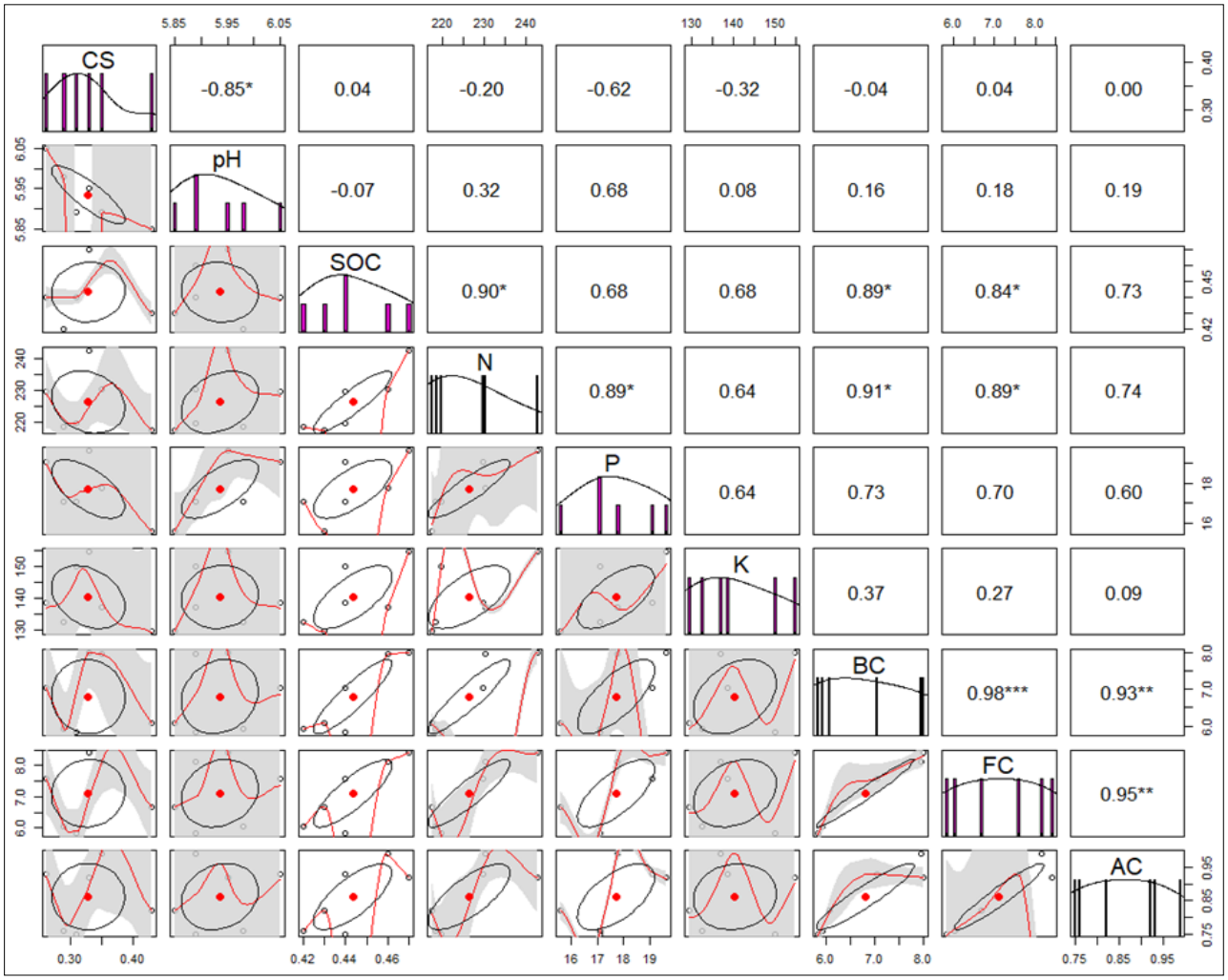


Fig. 3. Correlation analysis of key soil health parameters of natural farming practices. The parameters analyzed include, carbon sequestration levels (CS), soil pH (pH), soil organic content (SOC), nitrogen content (N), phosphorus content (P), potassium content (K), soil bacterial activity (BC), soil fungal activity (FC) and soil actinomycetes activity (AC). Significant correlations are denoted with asterisks (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$), highlighting key interdependencies among soil health parameters.

over CF, respectively, indicating a biologically enriched and resilient soil ecosystem. Although NF yields were 8 %–18 % lower (e.g. brinjal: 207 q/ha vs 232 q/ha in CF), the cost of cultivation was 12 %–14 % lower in NF, resulting in higher benefit–cost ratios (e.g., tomato: 2.92 vs 2.83 in CF). This economic advantage, coupled with environmental benefits, makes NF a strategically important practice for farmers, enhancing their resilience by reducing dependency on costly external input. The significant negative correlation between carbon sequestration and soil pH (r = -0.85*) emphasizes the role of NF in maintaining favorable pH for organic carbon retention. Overall, NF offers a dual advantage of improving long-term soil fertility and reducing dependency on synthetic inputs, thereby making it a strategic, climate-resilient alternative for sustaining vegetable productivity in coastal agro-ecosystems. The promotion and scaling up of natural farming practices, as supported by this study, can help achieve sustainable agricultural development in climatic vulnerable coastal areas like Odisha and similar agro-climatic regions of the country and beyond.

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Authors' contributions

PM[1] carried out conceptualisation, methodology and field experiment. DP was responsible for validation, investigation, writing and review. JS contributed to methodology, supervision, investigation, writing, review and editing. DMD provided resources, performed data analysis and wrote the manuscript. PM[2] contributed to conceptualization, methodology and editing. AH performed formal analysis, edited the original draft and prepared visualizations. BMR was involved in data collection and structuring of data, while BM conducted results analysis using statistical software. TKP supported field investigations, data interpretation and provided technical inputs on livestock-related components. AP contributed resources, data curation, writing and discussion. SLR conducted the literature review, prepared figures and tables and supported manuscript editing. All authors read and approved the final manuscript [PM[1] stands for Pradipta Majhi and PM[2] for Prasannajit Mishra].

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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