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A Case Study on Natural Farming as a Climate Adaptation Strategy for Banana: Enhanced Wind Resilience, Yield Stability, And Farm Profitability Under Field Conditions

Mahesha K N[1], Reshma A[2], Apoorva Guddaraddi[3], Upma Gamit[4], Mounica N[5], Sudheer Kumar P[6], Satya sree P[7], Baghele RD[8], Poojitha P[9], Bacham Shiva[10], Joshna Durga N[11], Manoj K N[12]

[1,9,10,11]Young Research Fellow, Rythu Sadhikara Samstha-APCNF, Andhra Pradesh
[2]Scientist, BRS, Pulivendula
[3,8]Assistant Professor, VNMKV, Parbhani
[4]Krishi Vigyan Kendra, Anand Agricultural University, Dahod
[5]Research Associate, BRS, Pulivendula
[6,7]Project Linked Associate, Rythu Sadhikara Samstha-APCNF, Andhra Pradesh
[12]Research Scholar, Dr. P.D.K.V, Akola

ABSTRACT: Extreme weather events, particularly high winds, have become increasingly frequent under changing climatic conditions, posing a major threat to banana production through lodging, plant damage, and substantial yield losses. Therefore, creating production systems that are climate robust is crucial to guaranteeing sustained banana farming. In comparison to conventional farming, the current field-based comparative case study assessed how well Andhra Pradesh Community-managed Natural Farming (APCNF) improved the wind resilience of bananas (Musa × paradisiaca L., cv. G-9). The study was carried out in adjacent fields at Lupatnutala village, Lingala Mandal, Andhra Pradesh, India, during the 2024–2025 cropping season under comparable agroclimatic circumstances. The conventional field represented the dominant production system, whereas the natural farming field had been continually managed for three years. The wind speed in both fields was 12.7 km/h during the research period. Crop resilience-related structural and soil-related characteristics were significantly enhanced by natural farming. When compared to conventional farming, pseudostem girth rose by 8.3%, root depth by 17.3%, and lateral root spread by 7.5%. The frequency of irrigation decreased from once every two days to once every four days due to a four-fold increase in earthworm abundance and significantly faster water infiltration. Superior fruit quality was demonstrated by the significantly greater soluble solids content (16°Brix) of fruits obtained under natural farming compared to those from conventional farming (9°Brix). Under natural farming, 45 plants per acre were injured while being exposed to the same wind event, whereas under conventional farming, about 520 plants per acre were destroyed, leading to a 31.33% yield loss. Consequently, natural farming produced approximately 35% higher yield, reduced cultivation costs by nearly 50%, and improved the benefit-cost ratio from 1.14 to 3.70. The findings demonstrate that continuous adoption of natural farming substantially enhances soil biological activity, root architecture, plant structural stability, resource-use efficiency, and economic returns, thereby improving the resilience of banana production under wind stress. This study

provides field-based evidence that natural farming represents an effective climate adaptation strategy for sustaining banana productivity and farm profitability under increasing climatic variability.

1. INTRODUCTION

Banana (Musa × paradisiaca L.; family Musaceae) is one of the world's most widely cultivated and economically significant fruit crops, contributing substantially to food security, nutritional well-being, and rural livelihoods in tropical and subtropical regions. The crop is valued for its high productivity, year-round fruit availability, and versatile utilization, making it an integral component of sustainable horticultural production systems. Originating from Musa acuminata and Musa balbisiana, this complex hybrid is native to Asia but is found throughout tropical portions of the world, especially in South and Southeast Asia and the western tropical Pacific Ocean [1-3]. India produced a total of 39.5 million tons of bananas. This makes India the number one producer of bananas in the world by a significant margin [4]. Production is concentrated in tropical and coastal regions. Andhra Pradesh is the largest producer by a significant margin, followed closely by Maharashtra, Karnataka, and Tamil Nadu [5]. However, the productivity and profitability of banana cultivation are increasingly threatened by the impacts of climate change, particularly the rising frequency and intensity of extreme weather events.

Among various climatic hazards, high wind events are one of the most destructive abiotic stresses affecting banana production. Owing to its succulent pseudostem, broad leaves, shallow root system, and large canopy, banana is inherently susceptible to lodging, pseudostem breakage, root failure, and bunch damage under strong winds. Wind-induced mechanical injury reduces the photosynthetic area, disrupts water and nutrient transport, impairs assimilate partitioning, and ultimately causes severe yield and quality losses. Economic losses become particularly pronounced when wind damage occurs during the reproductive or harvesting stages, when plants carry heavy bunches and their structural stability is compromised. Climate projections indicate that the frequency of extreme weather events, including storms and high winds, is expected to increase in many banana-growing regions, highlighting the urgent need for production systems that enhance crop resilience.

Conventional banana production relies heavily on synthetic fertilizers, pesticides, and intensive irrigation to maximize productivity. For banana plants to thrive, significant fertilization is usually necessary, especially with nutrients like nitrogen and potassium [6]. In addition to other improved cultural methods, the proper administration of vital nutrients is necessary to achieve high yields of excellent quality bananas. These components are regularly added to the soil, mostly by synthetic chemical fertilizers, to meet the nutritional needs of banana plants [7]. Banana possesses a relatively shallow and fibrous root system, with the majority of active roots confined to the upper soil layers. Consequently, the crop is highly dependent on surface soil moisture and nutrient availability, making it particularly susceptible to nutrient losses through leaching, volatilization, and denitrification, especially under intensive irrigation and fertilizer application. To compensate for these losses, conventional banana cultivation relies heavily on synthetic fertilizers, resulting in increased production costs and reduced input-use efficiency [8]. Moreover, the long-term and indiscriminate use of chemical fertilizers can adversely affect soil health by reducing biological activity, impairing soil structure, and diminishing water-holding capacity, ultimately weakening root development and plant anchorage. These changes may increase the susceptibility of banana plants to mechanical stresses, such as strong winds, thereby compromising crop productivity and stability. In the face of escalating fertilizer costs and increasing climate variability, there is a growing need for sustainable production systems that enhance soil health, improve resource-use efficiency, and strengthen crop resilience. Natural farming has emerged as a promising agroecological approach for sustainable crop production by minimizing external chemical inputs and promoting biologically active soils. Natural farming systems are one of the alternative production systems to address the priorities listed in the Food and Agriculture Organization's (FAO) report "The State of Food and Agriculture" (FAO2021). They primarily rely on biomass recycling, biological rejuvenation of natural nutrient cycles, and on-farm plant and livestock-based inputs. Natural farming systems are found to be inexpensive, provide farmers with freedom from purchased inputs, ensure comparable productivity, particularly in low-input crops, increase income, and be safe for the soil, plants, environment, and all life forms, including humans and animals, in addition to being non-degrading, non-depleting, and resource-conserving [9]. By lowering reliance on chemical inputs, increasing environmental sustainability, and boosting farmer wellbeing, natural farming offers a revolutionary approach to Indian agriculture. Low-cost methods that restore soil health, promote biodiversity, and guarantee productivity even in smallholder settings are the key to its success [10]. In India, the Andhra Pradesh Community-managed Natural Farming (APCNF) programme has demonstrated encouraging results in improving soil biological activity, enhancing nutrient cycling, increasing soil organic matter, conserving soil moisture, and reducing production costs. Improvements in soil structure and biological functioning under natural farming are expected to stimulate deeper root development, stronger rhizomes, and improved plant structural stability. Collectively, these changes may enhance the ability of banana plants to withstand wind-induced mechanical stress while maintaining productivity and fruit quality. However, despite the increasing adoption of natural farming, quantitative field-based evidence demonstrating its role in enhancing wind resilience in perennial fruit crops remains scarce.

The impacts of natural farming on crop productivity, soil fertility, microbial diversity, nutrient availability, and farm economics have been the main focus of earlier research. Understanding the mechanisms by which natural farming affects plant architecture, root system development, soil hydraulic characteristics, and structural stability under climatic pressures has received relatively little research. Specifically, there are few integrated field studies that connect resilience against wind damage in bananas with changes in soil biology, root architecture, plant structural features, and economic performance. In order to develop scientifically proven climate adaptation solutions that can lower production risks under increasingly changeable weather circumstances, it is imperative that this information gap be filled.

The present study was therefore undertaken to evaluate the influence of three years of continuous natural farming on the wind resilience of banana (Musa × paradisiaca L., cv. Grand Naine) by comparing adjacent natural and conventional farming systems exposed to the same natural wind event. To clarify the methods by which natural farming improves resilience, the study examined changes in soil biological activity, water infiltration, bulk density, root architecture, plant structural traits, fruit quality, yield stability, and farm economics. According to our hypothesis, ongoing natural farming improves structural stability, lessens crop damage from wind, maintains productivity, and increases farm profitability by strengthening the soil–root–plant continuity. This study offers field-based evidence that natural farming is a feasible climate adaptation method for resilient banana production under rising climatic variability by integrating agronomic, physiological, soil, and economic parameters.

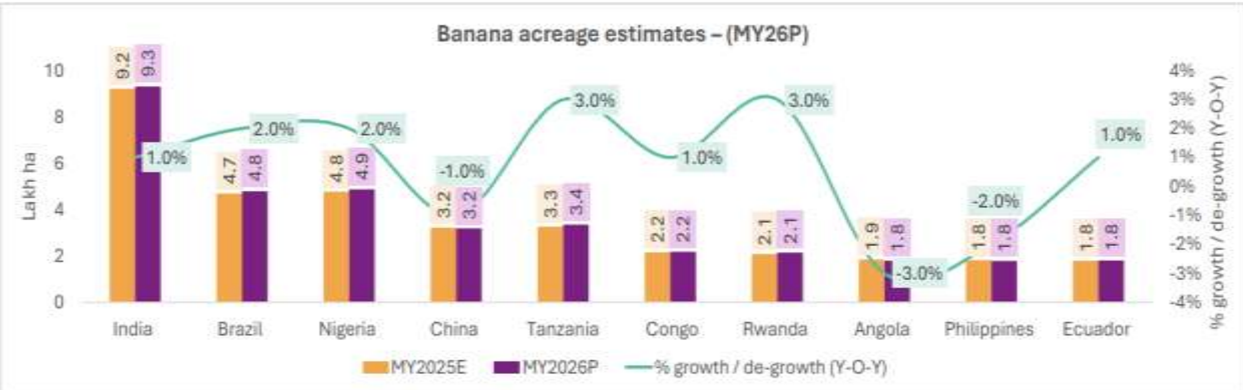

Fig. 1 Acreage estimates of major producing countries (APEDA-2026)

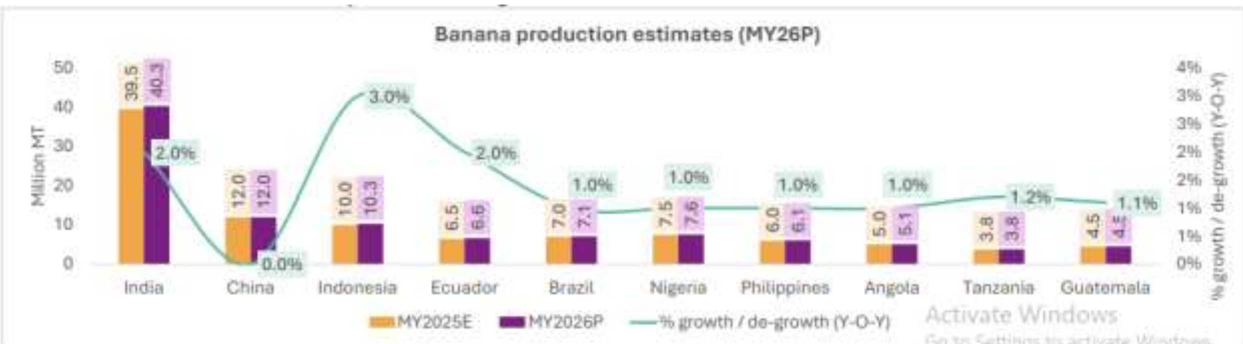

Fig. 2: Production Estimates of Major Producing Countries (APEDA-2026)

*MY26P- Marketing Year 26 Projected Value

2. MATERIAL AND METHODS:

The study was conducted during the 2024–2025 cropping season in Lupatnutala village, Lingala Mandal, Nandyal district, Andhra Pradesh, India, to evaluate the resilience of banana under natural farming (NF) and conventional farming (CF) following a naturally occurring wind event. Two adjacent farmer-managed fields located at 14.522136° N, 78.090621° E (NF) and 14.522075° N, 78.090722° E (CF) were selected to ensure comparable agro-climatic conditions. Both fields were cultivated with the banana cultivar Grand Naine (G-9) on black soil under drip irrigation, thereby minimizing variation due to genotype, soil type, and irrigation practices. The NF field had been managed continuously under Andhra Pradesh Community-managed Natural Farming (APCNF) practices for three years, whereas the CF field followed conventional crop management based on recommended chemical fertilizers and plant protection practices. Banana was planted on 10 June 2024 in the NF field and 20 May 2024 in the CF field, and observations were recorded at the harvesting stage after both fields were exposed to an identical natural wind event with a recorded wind speed of 37.1 km h^{-1} on 3rd of April 2025.

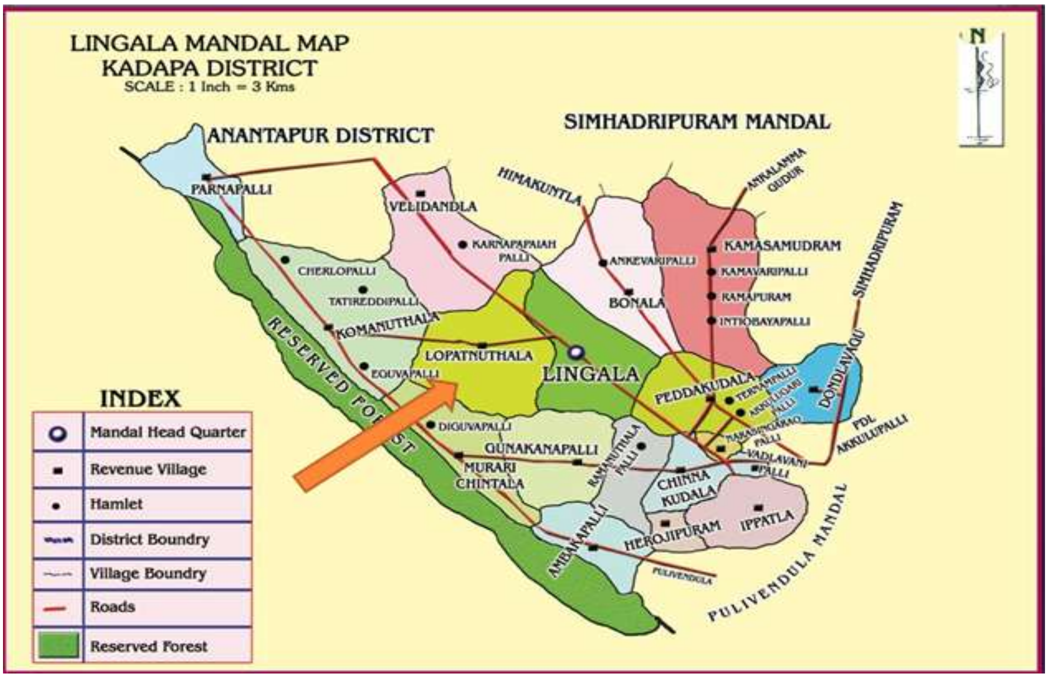

Fig. 3: Map showing the site of comparative study

Field observations were collected immediately after the wind event using standard horticultural procedures from representative plants selected in each field. Plant structural traits, including pseudostem height, pseudostem girth, rhizome girth, root depth, lateral root spread, number of functional leaves, and leaf area, were measured to assess mechanical stability and wind tolerance. Yield and fruit quality parameters included the number of hands per bunch, fingers per hand, fingers per bunch, finger length, finger girth, individual finger weight, bunch weight, estimated yield, and total soluble solids (°Brix), with soluble solids determined using a hand-held digital refractometer. Soil health was evaluated through earthworm abundance and water infiltration, where earthworms were counted within a 1 ft^2 sampling area and infiltration was determined as the time required for one litre of water to infiltrate into the soil. Wind damage was assessed by recording the number of damaged plants per acre, percentage yield loss, and estimated yield after the wind event. Irrigation frequency was documented from farmer records and field observations. Economic performance was evaluated using the cost of cultivation, gross income, net income, and benefit–cost (B:C) ratio, where net income was calculated as the difference between gross income and cultivation cost, and the B:C ratio was computed as the ratio of gross income to total cultivation cost. As the investigation was designed as a comparative field case study rather than a replicated experimental trial, the results were interpreted using descriptive statistics and percentage differences between farming systems to elucidate the relationships among soil health, plant architecture, wind damage, yield stability, and farm profitability under natural and conventional banana production systems.

Table 1. Site characteristics and management practices of natural and conventional banana production systems

Parameter	Natural Farming	Conventional Farming
Village	Lopatnutala	Lopatnutala
Mandal	Lingala	Lingala
District	Nandyal	Nandyal
Latitude	14.522136° N	14.522075° N
Longitude	78.090621° E	78.090722° E
Cultivar	Grand Naine (G-9)	Grand Naine (G-9)
Years under Natural Farming	3	0
Date of planting	10 June 2024	20 May 2024
Crop stage	Harvesting	Harvesting
Soil type	Black	Black
Irrigation method	Drip	Drip
Wind speed (km h^{-1})	37.1	37.1

3. RESULTS

3.1 Natural farming improved structural traits associated with wind tolerance

Despite being slightly shorter than conventionally grown plants, banana plants under natural farming exhibited markedly superior structural characteristics that are directly associated with mechanical stability. Pseudostem height was marginally lower under natural farming (181.2 cm) than conventional farming (184.3 cm), whereas pseudostem girth increased from 79.8 cm under conventional farming to 86.4 cm under natural farming, representing an 8.27% improvement. A thicker pseudostem provides greater mechanical rigidity and increases resistance to bending and breakage during high wind events. Conventional farming heavily utilizes synthetic nitrogen, which triggers rapid vegetative elongation. This often results in tall, top-heavy plants susceptible to wind-induced lodging (falling over). Natural and organic farming methodologies prioritize balanced, slower nutrient absorption. This results in slightly shorter plants with a lower center of gravity [11]. This growth pattern allocates biomass into the stem diameter and wall thickness rather than vertical height. Studies track this relationship through the "bending moment" of the plant; a shorter stature combined with a thick base exponentially reduces the mechanical stress placed on the plant during high winds. The lodging resistance is strictly governed by the accumulation of lignin, cellulose, and hemicellulose within the secondary cell walls of the stem [12]. The mechanical strength of a banana plant relies heavily on the quality of its structural carbohydrates [13]. Below-ground structural development was also substantially enhanced. Average root depth increased by 17.27%, from 63.7 cm under conventional farming to 74.7 cm under natural farming, while lateral root spread increased by 7.47% (156.6 to 168.3 cm). In addition, rhizome girth increased from 68 cm under conventional management to 82 cm under natural farming, indicating stronger subterranean support and greater storage capacity. Natural farming heavily emphasizes soil health, microbial diversity, and organic matter recycling. This soil environment optimizes the bioavailability of secondary nutrients like silicon (Si) [14]. Silicon deposits directly into the epidermal cells of the pseudostem, acting as a physical armor [15]. Natural farming treatments balance internal plant hormones, resulting in more structural anchoring roots per plant. This deep, widespread network prevents "root lodging"—where the entire plant topples out of the ground due to anchorage failure under lateral wind pressure [16, 17]. These improvements collectively suggest that continuous natural farming promoted a more robust plant architecture capable of resisting wind-induced lodging through enhanced anchorage and stem strength.

Table 2. Structural characteristics associated with wind resilience

Parameter	Natural Farming	Conventional Farming	% Change
Pseudostem height (cm)	181.2	184.3	-1.68
Pseudostem girth (cm)	86.4	79.8	+8.27
Rhizome girth (cm)	82.0	68.0	+20.59
Root depth (cm)	74.7	63.7	+17.27
Root spread (cm)	168.3	156.6	+7.47

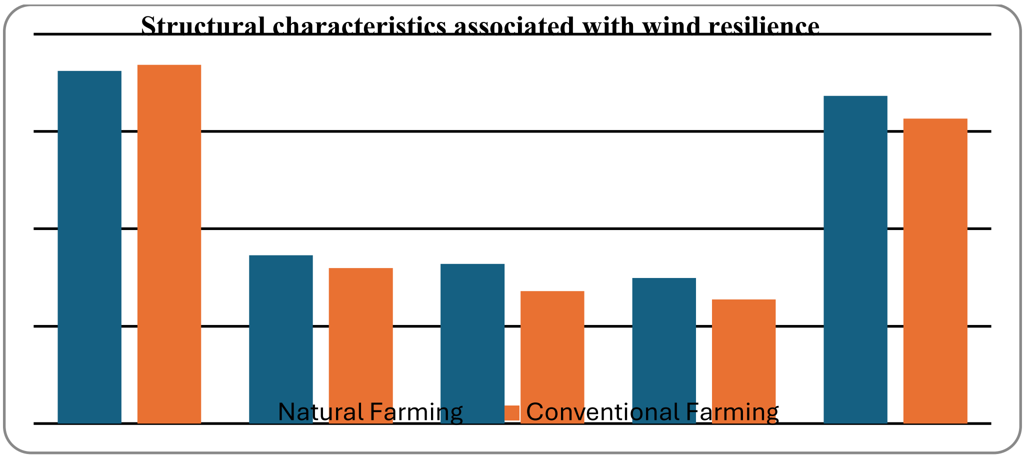

Fig. 4: Structural characteristics associated with wind resilience

3.2 Improved soil biological activity and hydraulic properties under natural farming

Pronounced differences were observed in soil biological and physical properties between the two farming systems. Natural farming supported four earthworms per square foot, compared with only one earthworm per square foot in the conventionally managed field, reflecting greater biological activity and improved soil ecological health.

Similarly, water infiltration was substantially faster in the natural farming soil. One litre of water infiltrated within 11.52 minutes under natural farming compared with 21.55 minutes under conventional farming. Faster infiltration indicates improved soil aggregation, greater macroporosity, enhanced pore continuity and superior soil structure, all of which facilitate root penetration and reduce runoff during rainfall events. These improvements translated directly into water-use efficiency. The natural farming field required irrigation only once every four days, whereas the conventional field required irrigation once every two days, indicating improved soil moisture conservation and reduced irrigation demand. Conventional agriculture relies on synthetic fertilizers and frequent tillage, which degrade soil organic matter, dry out topsoil, and physically disrupt or destroy earthworm populations. Natural farming reverses this trend by using constant organic mulching and bio-inoculants. This approach provides a steady, damp, shaded food supply and eliminates chemical toxins. As a result, earthworm counts and microbial biomass increase sharply [18]. Earthworm activity expands preferential flow depths from 33–46 cm up to 46–101 cm. Earthworm activity also altered key model parameters, notably the infiltration coefficient (k) and the decay exponent (α). The increase in k indicates enhanced initial infiltration capacity due to macropore development [19, 20]. Collectively, these observations demonstrate that three years of natural farming substantially improved the biological and hydrological functioning of the soil, thereby creating a more resilient root-zone environment.

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Table 3. Soil biological and physical properties

Parameter	Natural Farming	Conventional Farming	% Improvement
Earthworms (No. sq ft^{-1})	4	1	+300
Water infiltration (min L^{-1})	11.52	21.55	46.5% faster
Irrigation interval (days)	4	2	+100

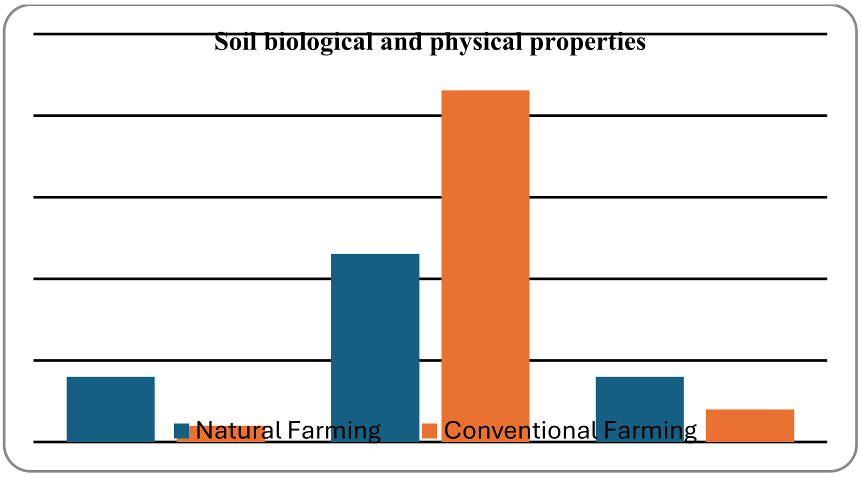

Fig. 5: Soil biological and physical properties

3.3 Enhanced physiological performance, fruit quality and yield

Natural farming maintained favourable canopy characteristics throughout crop development. Although leaves under conventional farming were slightly longer, the natural farming plants developed broader leaves providing a comparable photosynthetically active canopy. Fruit quality was markedly superior under natural farming. Soluble solids increased from 9°Brix under conventional farming to 16°Brix under natural farming, representing approximately a 78% improvement. Increased soluble solids indicate enhanced carbohydrate accumulation, suggesting that photosynthetic efficiency and assimilate translocation remained largely unaffected despite exposure to wind stress. The higher Brix values also indicate improved fruit sweetness and market quality, demonstrating that resilience under natural farming was achieved without compromising fruit quality.

Fruit yield components remained stable or improved under natural farming despite the wind event. Plants under natural farming produced 20.6 fingers per hand, representing a 5.10% increase over conventional farming (19.6 fingers per hand). Finger length increased marginally from 18.3 cm under conventional farming to 18.5 cm under natural farming (1.09% increase), while finger girth remained comparable between the two systems (3.2 vs. 3.3 cm). Although the number of hands per bunch was slightly lower under natural farming (12.3) than under conventional farming (12.6), the total number of fingers per bunch was higher (253.4 vs. 247.0), reflecting a 2.60% increase. Moreover, bunch weight increased from 26.0 kg under conventional farming to 29.0 kg under natural farming, corresponding to an 11.54% improvement. Based on bunch weight and the estimated number of fingers per bunch, the average individual finger weight was estimated at 114.45 g under natural farming compared with 105.28 g under conventional farming, representing an 8.71% increase. Leaf sap Brix, an indicator of plant photosynthetic efficiency and carbohydrate status, was substantially higher under natural farming (16 °Brix) than under conventional farming (9 °Brix), representing a 77.8% increase. The higher leaf sap Brix suggests improved carbohydrate accumulation, enhanced nutrient-use efficiency, and better physiological health, which may have contributed to stronger stems, improved recovery after wind stress, and greater yield stability. The high sugar accumulation in vegetative tissues provides the building blocks for structural carbohydrates, including cellulose, hemicellulose, and lignin. This process leads to thicker cell walls and denser vascular bundles. When wind stress hits, plants with concentrated leaf sap possess superior osmotic potential.

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This fluid density prevents cellular collapsing (plasmolysis) and hydraulic cavitation when high winds physically bend the pseudostem, accelerating post-storm structural recovery.

The most striking difference was observed in crop survival following the wind event. Only 45 plants were damaged across the entire 4.5-acre natural farming field, whereas 520 plants were damaged across the 5-acre conventional farming field under the same wind conditions. Despite the occurrence of limited damage in the natural farming field, the affected plants remained productive and no measurable yield loss was recorded. Consequently, estimated productivity reached 27.8 t $acre^{-1}$ under natural farming compared with 20.6 t $acre^{-1}$ under conventional farming, representing an approximately 34.95% increase in yield. In contrast, the conventional farming system experienced a 31.33% reduction in yield following extensive wind damage. These findings demonstrate that natural farming substantially improved crop resilience by maintaining bunch integrity, enhancing fruit quality, and minimizing productive losses under climatic stress, thereby ensuring greater yield stability than the conventional production system.

While conventional methods maximize finger length and bunch weight using synthetic inputs like potassium nitrate or growth regulators, these elongated fruits are fragile. Wind-swept conventional fields often suffer from severe fruit friction, skin scarring, and bunch detachment [21]. In contrast, natural farming practices generate compact bunches with thick finger girths. This cellular density protects the fruit during storms [22].

Table 4: Effect on physiological performance, fruit quality and yield of banana under NF and CF

Parameter	Natural Farming	Conventional Farming	% Change (NF vs CF)
Fingers per hand	20.6	19.6	+5.10
Finger length (cm)	18.5	18.3	+1.09
Finger girth (cm)	3.2	3.3	−3.03
Individual finger weight (g)	104.4	95.2	+8.71
Hands per bunch	12.3	12.6	−2.38
Fingers per bunch	253.3	246.9	+2.60
Bunch weight (kg)	29.0	26.0	+11.54
Total soluble solids (°Brix)	16.0	9.0	+77.78
Estimated yield (t $acre^{-1}$)	27.8	20.6	+34.95

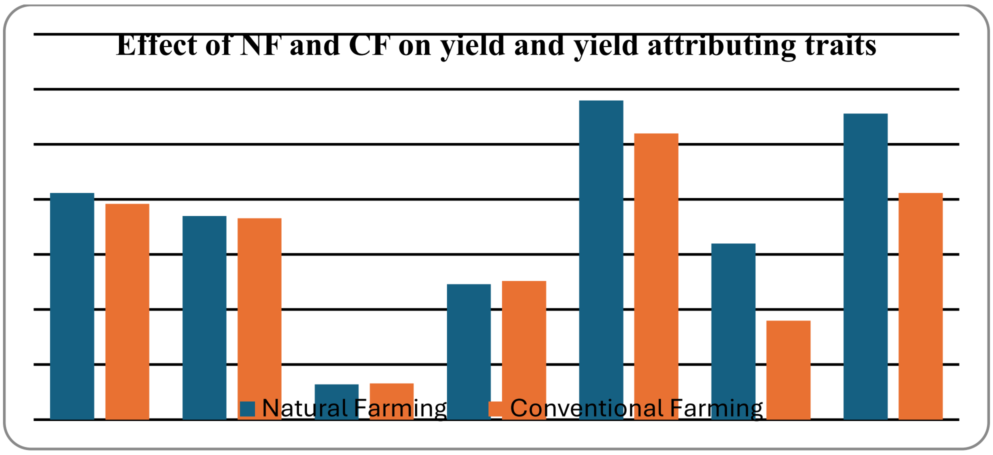

Fig. 6: Effect of NF and CF on yield and yield attributing traits

3.4 Economic benefits of natural farming

The agronomic advantages observed under natural farming translated directly into superior economic performance. The cost of cultivation was reduced from ₹151,800 per acre under conventional farming to ₹75,000 per acre under natural farming, representing a reduction of approximately 50%. Despite substantially lower production costs, gross income increased from ₹200,000 to ₹230,000 per acre. Consequently, net income increased from ₹48,200 under conventional farming to ₹155,000 under natural farming, corresponding to an increase of more than 220%. Similarly, the benefit-cost ratio improved dramatically from 1.14 to 3.70, confirming that natural farming was not only biologically resilient but also economically sustainable under adverse climatic conditions.

Table 6. Economic analysis

Parameter	Natural Farming	Conventional Farming	% Difference
Cost of cultivation (₹ acre^{-1})	75,000	151,800	−50.59
Gross income (₹ acre^{-1})	230,000	200,000	+15.00
Net income (₹ acre^{-1})	155,000	48,200	+221.58
Benefit : Cost ratio**	3.07	1.32	+132.58

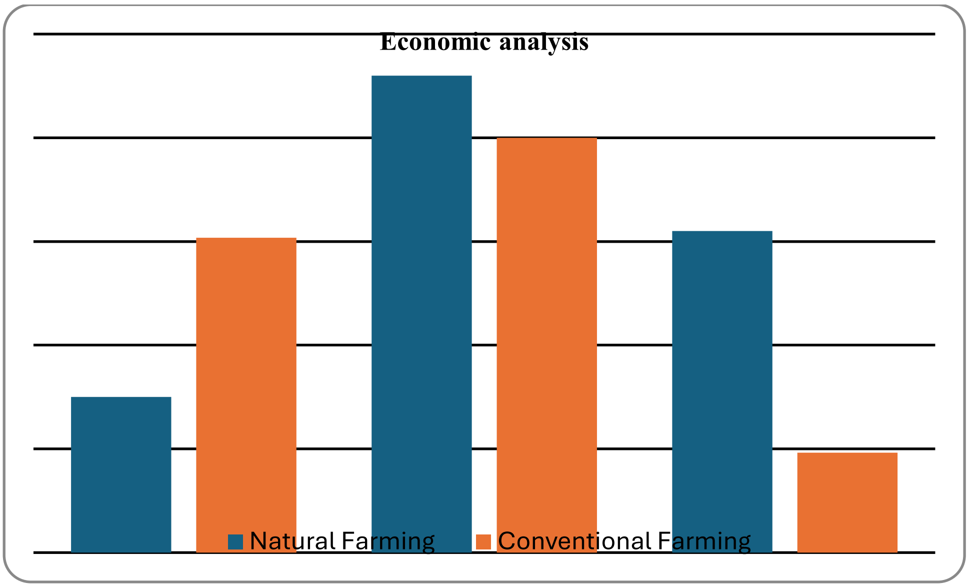

Fig. 7: Economic analysis under NF and CF

4. CONCLUSION:

The current case study showed that, in comparison to the standard production technique, natural farming significantly increased the banana's resistance to wind-induced damage. The natural farming field had significantly less plant damage (45 plants spread over 4.5 acres) than the conventional farming area (520 plants spread over 5 acres) while being exposed to the same wind event. Greater resistance to lodging and pseudostem breaking resulted from natural farming's superior growth, stronger plant architecture, and improved root development. Under natural farming, yield parameters such as fingers per hand, bunch weight, individual finger weight, and total fingers per bunch were either maintained or improved. This led to an estimated yield of 27.8 t acre^{-1}, which is roughly 35% greater than the 20.6 t acre^{-1} observed under conventional farming. Additionally, increased physiological state and carbohydrate buildup were indicated by higher leaf sap °Brix values under natural farming, which may have contributed to improved stress tolerance and recovery after the wind event.

Overall, the results indicate that natural farming improves crop stability by boosting plant vigor, soil health, and tolerance to extreme weather events in addition to sustaining banana yield under challenging climatic conditions. These findings demonstrate the promise of natural farming as a climate-resilient banana producing method. However, since this study is a single-event field case study, more multi-location and multi-season research in different environmental settings is needed to confirm these results and measure the long-term advantages of natural farming for climate adaptation and sustainable banana production.

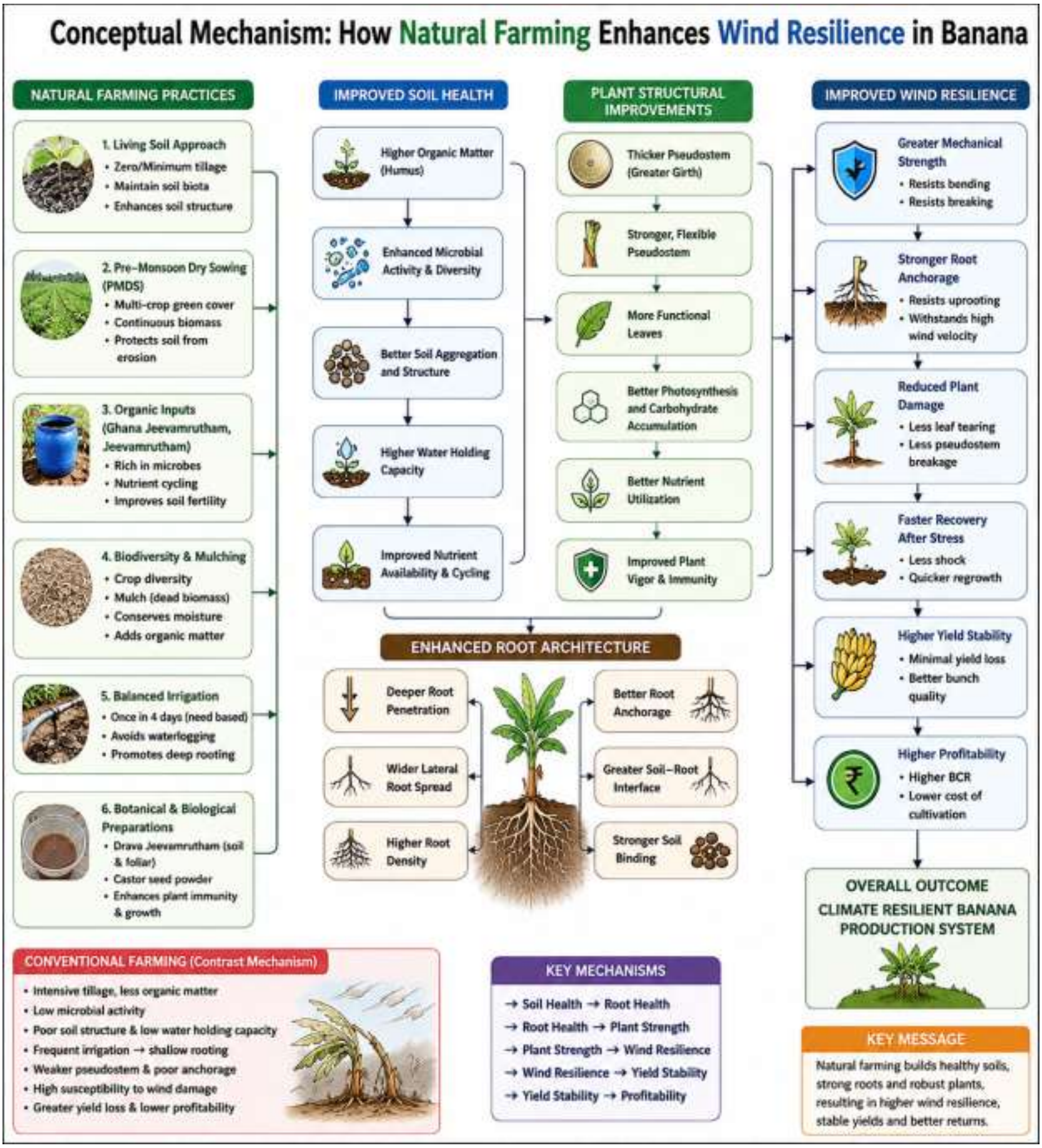

Fig. 2: Conceptual mechanism for wind resilience through natural farming

Authors' contributions

Mahesha KN, Reshma A, Sireesha Y conceived the topic, conducted the literature survey, performed data compilation and critical analysis, prepared the original draft, and coordinated the manuscript preparation. Apoorva, Mounica, Upma, Poojitha, Joshna, Shiva, Sudheer, Satya and Manoj contributed to the critical review of the literature, manuscript revision, and intellectual input. Mahesha K N and Baghele RD assisted in the preparation of tables, figures, formatting, and proofreading. Mahesha KN, Sudheer, and Satya supervised the work, provided technical guidance, critically revised the manuscript, and approved the final version. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no known competing interest.

Ethical issues: No

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this review article, the authors used AI-assisted language tools (including Grammarly for grammar and language editing and ChatGPT for improving language clarity and readability). These tools were used solely to enhance the quality of written expression.

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