

ASSESSING SOIL MICROBIAL POPULATION AND NUTRIENT DYNAMICS FOR ENHANCING PRODUCTIVITY IN MILLET-BASED CROPPING UNDER NATURAL FARMING

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ABSTRACT

Soil microorganisms are vital components of the soil ecosystem, playing an important role in nutrient cycling, organic matter decomposition, and maintaining soil fertility and productivity. In recent years, growing concerns about soil degradation and the excessive use of chemical inputs have increased interest in sustainable farming approaches that support soil health. Natural farming is gaining recognition as an eco-friendly agricultural practice that encourages biological activity in the soil and enhances the natural functioning of agroecosystems. Since soil microbial populations are considered sensitive indicators of soil health, understanding their response to different management practices is essential. Therefore, the present study was conducted to evaluate the effect of different cropping systems and natural farming practices on soil bacterial and fungal populations, with the aim of assessing their potential to improve soil biological health and promote sustainable crop production. The specific objectives of this study were i) To identify the most productive millet-based cropping system under natural farming practices, ii) To study the effect of different millet-based cropping systems on physico-chemical and biological properties of soil under natural farming practices, iii) To assess the radiation use pattern of different millet-based cropping systems under natural farming practices. The experiments were conducted under split plot design using 48 plots and soil samples were collected from each of the treatment plot before sowing and after harvest of every cropping system and analyzed for soil physico-biological properties. Further, the yield and features of the finger millet, barn yard millet, lentil and linseed were found to improve considerably due to natural farming practices associated with millet cropping systems. Initial bacterial and fungal populations were 22.29×10^{-8} and 10.0×10^{-5} CFU g⁻¹ soil, respectively. At harvest, natural farming treatments improved microbial populations, with NF₄ recording the highest bacterial (26.2×10^{-8} CFU g⁻¹ soil) and fungal (12.7×10^{-5} CFU g⁻¹ soil) counts. Among the natural farming levels, application of NF₄ recorded significantly higher available soil nitrogen (210 kg ha⁻¹), phosphorus (23.1 kg ha⁻¹), and potassium (81.1 kg ha⁻¹) compared to NF₁ (Nitrogen-179 kg ha⁻¹, phosphorus- 20.1 kg ha⁻¹, and potassium- 68.3 kg ha⁻¹) and for the cropping systems, CS₁ recorded significantly higher kharif grain yield (1207 and 1130 kg ha⁻¹) and rabi grain yield (644 and 534 kg ha⁻¹), respectively in 2024-25 and 2025-26 compared to CS₄ (kharif grain yield- 310 and 305 kg ha⁻¹ and rabi grain yield- 343 and 324 kg ha⁻¹, respectively). Thus, advanced natural farming practices improve considerably microbial activity and soil health. Finally, yields of millet, lentil and linseed crops were evaluated. It can be stated that the application of natural farming significantly enhanced soil nitrogen content and improved the growth of crop species. Positive correlations were found between microbial parameters and millet yield, which proves that the management of soil microbes can contribute to the efficiency of nitrogen utilization and productivity.

KEYWORDS: natural farming; Beejamrit; Jeevamrit; Ghanajeevamrit; soil microbial population; nutrient dynamics; millet-based cropping system

INTRODUCTION

Natural farming has turned out to be one of those environmentally sustainable agricultural methods that rely little on chemical inputs and support biological processes occurring in the soil. Success in natural farming greatly relies upon the presence of beneficial soil microorganisms that help transform nutrients, make them more readily available, and contribute to improving soil health. According to recent research, natural farming

practices may favor microbial diversity, enhance microbial associations, and positively influence the functional ability of soil microbes. It turns out that natural farming is an ecologically based farming method that requires low quantities of chemicals and synthetic fertilizers and encourages organic materials locally available, crop residue recycling, and stimulating biological processes in the soil [6]. All the techniques could result in providing good conditions for microbes, promoting nutrient cycling, and maintaining soil fertility. Millet-based agriculture fits natural farming perfectly due to the resilience of millets to climate change, their nutritional value, and ability to grow under marginal conditions [4]. Nevertheless, there is a challenge of poor soil fertility, specifically nitrogen deficit, which could be an obstacle for boosting production. Bacteria and fungi belong to the major microbial groups that inhabit soils and participate actively in decomposition and nitrogen mineralization, thus regulating soil biological balance. The population of bacteria and fungi is commonly considered as an index of soil biological fertility and the quality of sustainable practices. This means that studying changes in the populations of bacteria and fungi due to application of different farming practices can be helpful in analyzing soil ecosystem functions and sustainable agriculture. While there is a lot of evidence about the effect of soil microflora on nutrient cycling, very little is known about their contribution to nitrogen availability and productivity of crops in natural farming practices based on millets. That is the reason for conducting this research.

MATERIAL AND METHODS

Field experiment on Assessing soil microbial population and nutrient dynamics for enhancing productivity in millet-based cropping under natural farming Systems has been carried out in 2024-25 and 2025-26 on Natural Farming farm at RPCAU Pusa Samastipur (848125) Bihar. The experimental site soil type is Sandy Loam, having high pH value of 8.29, Moderate OM value is 0.55, Low nitrogen content is 199 kg ha⁻¹, phosphorus is 21.8 kg ha⁻¹ and potassium is 76.3 kg ha⁻¹. The experiment place is RPCAU, Pusa, Samastipur, Bihar. Latitude: 25.98° Longitude: 85.67° E Altitude: 52 m above mean sea level, Sub-humid Subtropical Monsoon Climatic Condition. About 80-85% annual precipitation is received in June to September period. Average Annual Rainfall varies between 1140-1260 mm per year. Maximum temperature may reach up to 45°C during the summer season and 7-11°C during winter seasons. This experiment has been conducted using a split plot design which comprises of four cropping systems in main plots and four natural farming treatments in sub-plots. The cropping systems are finger millet-linseed (CS1), finger millet-lentil (CS2), barnyard millet-linseed (CS3), and barnyard millet-lentil (CS4). The natural farming methods used include Control (NF1), Jeevamrit (NF2), Beejamrit+Jeevamrit (NF3), and Beejamrit+Jeevamrit+Ghanajeevamrit+Mulching (NF4). Available soil macronutrients were analyzed using standard analytical procedures. Available nitrogen (N) was determined by the alkaline potassium permanganate method using a Kjeldahl distillation unit [22]. Available phosphorus (P) was extracted using 0.5 M NaHCO₃ (pH 8.5) and estimated colorimetrically using a UV-Visible Spectrophotometer at a wavelength of 660 nm [23]. Available potassium (K) was extracted with neutral normal ammonium acetate (1N NH₄OAC (pH 7.0)) and quantified using a Flame Photometer [24]. The microbial population in the soil was assessed through serial dilution and plating technique [7], where 10 g of soil sample was suspended in 90 mL of sterile distilled water in a 150 mL conical flask, followed by subsequent serial dilutions and plating onto specific growth media. The dilutions of 10⁻⁷, 10⁻⁵ were used for bacteria and fungi, respectively. The colony appeared on petriplates were counted by using colony counter and average colony of three plates used for calculations. According to an earlier study [13], the application of Jeevamrita in the zero-budget natural farming system proved beneficial as far as soil parameters and biology were concerned, and this finding is in line with the notion that microbial applications could play an essential role in enhancing soil nutrients. As per the natural farming recommendations of the Indian government, Beejamrit acts as seed coat for natural farming purposes for protecting the seeds. The different data gathered for various traits was analyzed statistically via the method of analysis of variance. The experimental data were subjected to Analysis of Variance (ANOVA) applicable to a split-plot design using the R statistical computing environment via RStudio. The main plot factor consisted of four cropping systems, and the sub-plot factor consisted of four natural farming levels. The significance of differences among the treatment means was evaluated using the Least Significant Difference (LSD) test at 5% level of probability (p=0.05).

RESULT AND DISCUSSION:

1) Soil nitrogen availability and nutrient dynamics:

Effect on initial nitrogen content: The initial soil available nitrogen content was 199 kg ha⁻¹, showing that there was low to medium available soil nitrogen status. Among the various essential elements, nitrogen is a very limiting element for crop growth and productivity, especially for cereals. The lower amount of soil nitrogen can be due to low soil organic carbon content, which was found to be only 0.55%. Soil organic matter has been reported to be the source of nitrogen in the soil. With this kind of soil nitrogen status, increased microbial activity using natural farming techniques can lead to the mineralization of the nitrogen from decomposing organic residues, thereby increasing available nitrogen in the soil. Increased soil nitrogen content under natural farming practices is associated with increased organic matter decomposition and mineralization. The higher soil nitrogen availability with millets could be due to increased soil biological activity because an earlier study [16] observed that higher soil available nitrogen was associated with organic and microbial biomass carbon with

finger millet cultivation in natural practices. In addition to this, the increased availability of nitrogen due to the natural farming using millets can also be attributed to the use of organic nutrients as finger millet and foxtail millet cultivated using organic nutrients have been shown to be under moderate availability of nitrogen in an earlier study [21].

Final soil nitrogen availability: The available nitrogen in the soil was significantly affected by both cropping systems and natural farming practices (Table 1; Fig. 1). In case of the cropping system, the highest level of available nitrogen was found in CS4, which contained 195 kg/ha of available nitrogen and was significantly higher than CS1 (190 kg/ha), CS2 (192 kg/ha) and CS3 (191 kg/ha). Increased available nitrogen in CS4 might be due to effective nutrient cycling, contribution of roots in biomass, and microbial activity in the system. Natural farming practices showed a strong impact on available nitrogen in soil. The highest level of available nitrogen (210 kg/ha) was observed in NF4, while 199 kg/ha, 189 kg/ha, and 179 kg/ha were the available nitrogen in NF3, NF2, and NF1 respectively. Advanced natural farming practice increased available nitrogen in soil due to enhanced mineralization of organic matter, increased microbial populations, and increased biological transformations of nitrogen. Previous studies also reported that advanced natural farming practice had significantly increased available nitrogen levels in the soil by improving the nutrient cycle through increased microbial activity in the soil. Increased residual soil nitrogen under advanced natural farming practices might be due to increased organic matter decomposition and enhanced mineralization of nitrogen because of increased microbial population. Higher soil nitrogen availability under natural farming may also be due to more overall effects of agroecological transitions, where an earlier study [19] showed that the higher the degree of transition towards natural farming in farms located in central India, the higher is the level of total soil nitrogen. The higher nitrogen levels available from the millets systems might also have something to do with the incorporation of residues and organic inputs, seeing how the IIMR organic farming in millets report describes the process of organic production of millets as one that facilitates biological processes that involve soil organisms and, thus, nitrogen availability.

2) Soil Phosphorus availability and nutrient dynamics:

Initial soil phosphorus availability: Available phosphorus in the soil was 21.8 kg P₂O₅ ha⁻¹ that can be categorized as moderate fertile soil. In the case of alkaline soil, the availability of phosphorus may be constrained because it tends to get fixed by calcium compounds. This experiment used soil with a pH value of 8.29 which could possibly reduce the availability of phosphorus to plants. The involvement of soil microorganisms such as phosphate solubilizers plays a significant role in transforming unavailable phosphorus into readily available forms for plants. Thus, improvements in microbial communities from natural farming techniques might help increase phosphorus availability for plants. Higher phosphorus availability in soils with advanced natural farming could be due to better organic matter decomposition and nutrient recycling. An increase in the soil availability of phosphorus in organic farming could further be supported by increased solubilization of indigenous phosphorus by microorganisms since, according to an earlier study [12], phosphorus solubilizing microorganisms make indigenous soil phosphorus soluble by natural solubilization processes. Improved phosphorus availability in the millet system due to eco-farming practices could be due to higher phosphate-solubilizing microbial activity, and this is because, according to an earlier study [15], phosphorus solubilizing microorganisms facilitate the solubilization of insoluble phosphorus in sustainable agriculture. Better phosphorus efficiency within millet production systems may similarly be related to benefits associated with organic nutrient management, as indicated by the findings of an earlier study [21] which found favorable productivity results for both finger and foxtail millets using organic nutrient management approaches.

Final soil phosphorus availability: The available phosphorus was influenced significantly by the crop management practices and natural farming levels used (Table 1; Fig. 2). Under different cropping systems, CS4 showed the highest available phosphorus level at 21.8 kg P₂O₅ ha⁻¹, while CS2 came second at 21.7 kg P₂O₅ ha⁻¹, followed by CS3, which had the lowest value at 21.3 kg P₂O₅ ha⁻¹. While differences were minimal, the statistical significance indicates that the crop management systems had an influence on phosphorus. The natural farming treatments used significantly influenced the availability of phosphorus in the soils. The treatment with the highest available phosphorus level was NF4 at 23.1 kg ha⁻¹, followed by NF3 (22.0 kg ha⁻¹), NF2 (21.0 kg ha⁻¹), and NF1 (20.1 kg ha⁻¹). This could have been caused by the activities of phosphate-solubilizing microorganisms and production of organic acids during organic matter decomposition, thus making more phosphorus available to plants. This is a common phenomenon under biological farming systems. The ecological basis of greater available phosphorus under low-input millet systems is also supported by microbial ecology research, because an earlier study [9] highlighted that phosphate-solubilizing microorganisms help resolve phosphorus limitation while improving soil function in sustainable agriculture.

3) Soil Potassium availability and nutrient dynamics:

Initial soil potassium availability: Potassium available in the soil was found to be 76.3 kg K₂O ha⁻¹, which shows that the potassium level was quite low in the soil. Potassium plays a vital role in enzyme activation, regulating water and stress resistance in plants. Since the potassium level was low, it could help the process of nutrients recycling using the residues of crops and the process of mineralization through microbial action. Microbes present in the soil can help to increase the potassium availability in soil through the release of organic acids and solubilization of potassium bearing rocks. Potassium availability being more at an advanced natural farming system could be due to increased addition of organic matter, microbial action leading to increased

potassium availability in soil. Higher potassium availability in such farming systems could also be because an earlier study [16] reported that finger millet under organic and natural production systems showed higher available N, P, and K along with higher microbial biomass carbon than conventional production.

Final soil potassium availability: While cropping systems had no meaningful effect on the total amount of extractable potassium, cropping system four did produce the highest value ($74.9 \text{ kg K}_2\text{O ha}^{-1}$) and cropping system one had the lowest ($74.4 \text{ kg K}_2\text{O/ha}$) (Table 1; Fig. 3). The lack of an effect on potassium levels indicates that potassium levels remained reasonably constant between cropping systems during the study period. In contrast, natural farming treatments had a meaningful effect on the total extractable potassium levels available. The highest level of extractable potassium was found under natural farming treatment 4 ($81.1 \text{ kg K}_2\text{O/ha}$) followed by treatment 3 ($76.6 \text{ kg K}_2\text{O/ha}$), treatment 2 ($72.5 \text{ kg K}_2\text{O/ha}$) and treatment 1 ($68.3 \text{ kg K}_2\text{O/ha}$). The greater amount of potassium available under natural farming treatments is attributed to the enhanced decomposition of organic matter and the subsequent solubility of potassium bearing minerals through microbial action. improved biological activity under natural farming likely contributed to greater nutrient release and retention in the soil. the interaction between cropping systems and natural farming treatments ($m \times s$) was non-significant for available nitrogen, phosphorous and potassium, indicating that nutrient availability response of natural farming practices is consistent across all cropping systems. the higher residual potassium under advanced natural farming levels can be attributed to improved organic matter additions, enhanced microbial activity, and greater release and retention of exchangeable potassium in soil. the improvement in soil k status under natural farming was also associated with stronger internal nutrient cycling. as noted in an earlier study [14], organic-natural input-based nutrient managements improve soil biological activity and support enhanced nutrient availability in low-input production systems. more potassium availability in millet systems under residue retentive managements could come from less K mining/more re-cycling crop residue. An earlier study [3] highlighted how inadequate K replenishment will lead to negative k balances for indian cropping systems; thus, residue-based and indigenous k managements are critical mitigating strategies. the positive effect of potassium availability through natural farming could be attributed to the found on microbial mobilization of non-exchangeable k in an earlier study [17], which indicated that there are potassium solubilizing microorganisms that are able to liberate k from soil minerals to available plant forms via the production of acids. the increased available k together with a cumulative effect of organic matter additions on available K in finger millet an earlier study [1] showed that organic sources were able to increase available nitrogen, phosphorus and potassium in a finger millet system by way of FYM and other organic sources would also increase available nitrogen, phosphorus and potassium in a finger millet system.

Soil Microbial Population under Cropping Systems and Natural Farming:

1) Initial Soil Bacteria count: Soil bacteria were at a starting count of $22.29 \times 10^8 \text{ CFU g}^{-1}$ soil and can be characterized as either the most abundant category of soil microorganisms, and they play a large role in decomposing organic matter, mineralizing nutrients, maintaining the quality of soil and supporting biological processes in the soil through the activities of soil biota. The amount of bacteria recovered is indicative of the activity of a microbial population that produces biological processes in the soil. Microbial activity in soil is very important in natural farming systems because microbial transformation of nutrients is primarily what allows for nutrient cycling that occurs naturally without the use of any external chemicals or fertilizers. There is evidence that the increased counts of bacteria that was recovered from soils under the advanced natural farming treatments was due to the addition of more organic matter to soils, increasing the availability of substrate for bacteria to multiply on, and creating a better rhizosphere for bacterial multiplication to occur in. A large portion of the reason for the increased numbers of bacteria that were found in soils under natural farming systems may also be attributed to better soil health and an increase in microbial activity. since an earlier study [5] showed that natural farming treatments increased soil health indicators, available nutrients, and microbial enzyme activities over conventional farming. The effect of cropping systems on soil bacteria may also be mediated through residue retention and reduced disturbance, as an earlier study [2] reported that tillage and residue management practices enhanced soil biological attributes and supported microbial diversity in long-term systems.

2) Final Soil Bacteria count: Both cropping systems (CS) and natural farming (NF) treatments did not have a statistically significant influence on total bacterial abundance in soil (Table 2; Fig. 4). With respect to CS, the highest bacterial populations were associated with CS4 ($24.0 \times 10^8 \text{ CFU g}^{-1}$ of soil), CS2 ($23.9 \times 10^8 \text{ CFU g}^{-1}$ of soil), and CS3 ($23.8 \times 10^8 \text{ CFU g}^{-1}$ of soil), whereas the lowest was associated with CS1 ($20.6 \times 10^8 \text{ CFU g}^{-1}$ of soil). While CS treated bacterial populations revealed numerical differences, they were statistically non-significant. With respect to NF treatment levels, the highest bacterial populations occurred under the NF4 treatment level ($26.2 \times 10^8 \text{ CFU g}^{-1}$ of soil), followed by NF3 ($24.6 \times 10^8 \text{ CFU g}^{-1}$ of soil), NF2 ($23.0 \times 10^8 \text{ CFU g}^{-1}$ of soil), and NF1 ($21.6 \times 10^8 \text{ CFU g}^{-1}$ of soil). Increasing bacterial populations under higher levels of NF treatment were attributed to improved levels of available organic substrates and more favorable soil environments for microbial growth; however, there were no significant differences among treatments or between treatment interactions (CS x NF). Therefore, it appears the expected differences in bacterial population growth due to advanced levels of NF treatment, resulted from long-term continuous organic matter addition, resulting in greater substrate availability and a more favorable soil environment for microbial growth. The beneficial effect of improved management has influenced soil bacterial growth in the NF system. since an earlier

study [18] showed that natural farming improved microbial nutrient-cycling potential, diversity, and microbial networks in comparison with conventional farming.

3) Initial Soil Fungi Count: Initially, the total fungal population in the soil was 10.0×10^5 CFU g⁻¹ soil. Fungi decompose complex organic matter, form humus, and recycle nutrients, as well as help bind soil together and improve soil structure through the creation of fungal hyphae and other binding agents. The measured fungal population indicates that, even in alkaline soils, there is a potential for active microbes to thrive and contribute to increased fungal activities in the soil through natural farming practices will increase nutrients available for sustainable crop production by facilitating organic matter decomposition and turnover. A greater amount of fungal growth associated with different stages of advanced natural farming practices suggests that soil habitat has improved, more organic residue has been added to soil, and there is more decomposable substrate available for fungi to grow than prior to advancing natural farming practices. Further, differences in fungal dynamics observed in the different cropping systems may be related to changes in fungal population composition as well as functional changes within soils. because an earlier study [8] reported that crop diversification, particularly legume-based diversification, improved soil health and that shifts in fungal communities were pivotal for maintaining soil functions. The positive response of soil fungi under natural or biologically managed systems may be linked with reduced chemical disturbance and greater recruitment of beneficial fungi, since an earlier study [10] found that organic farming enhanced fungal diversity and recruited beneficial fungal groups compared with conventional management.

4) Final Soil Fungi Count: The effect of cropping systems on fungal population was not statistically significant, but natural farming treatments have significantly affected fungal population. The highest fungal population was present under CS4 (11.6×10^5 CFU g⁻¹ soil), followed by CS2 (11.5×10^5 CFU g⁻¹ soil), CS3 (11.4×10^5 CFU g⁻¹ soil) and lastly CS1 (10.4×10^5 CFU g⁻¹ soil) which all had no significant differences statistically. In contrast, natural farming treatments were found to have significantly greater fungal populations than all other treatments. NF4 had the greatest fungi population (12.7×10^5 CFU g⁻¹ soil), compared to NF3 (11.9×10^5 CFU g⁻¹ soil), NF2 (11.1×10^5 CFU g⁻¹ soil) and NF1 (10.3×10^5 CFU g⁻¹ soil) where NF4 was significantly different than the other NF treatments. The greater level of fungal population seen in NF4 is due to (1) increased decomposition; (2) improved conditions; and (3) improved soil biological activities under natural farming systems. Because fungi are responsible for decomposing plant and animal residues and cycling nutrients, an increase of fungi generally indicates an improvement of soil's biological health. Organic residue addition to soil at an advanced level of natural farming will improve the quality of the organic material added and increase the habitat for fungi, providing more substrates for fungal growth and reproduction. The presence of an increase in fungi under ecologically managed treatments may also be due to enhanced nutrient cycling dependent on the presence of decomposing organic matter present. as an earlier review [20] noted that crop residue management strongly affects soil health processes in cereal-based systems, including the microbial environment that supports decomposition and nutrient turnover.

3) Influence of cropping systems and natural farming practices on grain and straw productivity of millets, lentil, and linseed

3.1 Finger Millet/Barnyard Millet

Grain Yield (kg ha⁻¹)

Various methods of planting and how the crop was cared for have greatly changed how much finger millet and barnyard millet (grain) can grow (Table 3; Fig. 5). The average amount of harvested grain (yield) for these two crops grown in 2024 ranged from 310 kg (CS4NF1) to 1,207 kg (CS1NF4) and for being grown in 2025 it ranged from 305 kg to 1,130 kg accordingly. In every method of planting used, the highest yields were found in the CS1NF4 treatment followed by CS2NF4. The lowest recorded yields were found under CS4NF1 for both years of yield testing. The average yield of grain increased with the nutrient levels being used (NF1-NF4). Under CS1, yields increased from 587 to 1,207 kg/ha. Under CS1 in the following year of growing the same crop yields went from 443 to 1-130/ha. The same pattern was observed in yields under CS2, CS3, and CS4.

The large amount of harvested grain found under the CS1NF4 treatment could be attributed to more nutrients being available for the growing crop, increased biomass, higher number of existing functional leaves (more sunlight to photosynthesize), and a greater efficiency of transporting materials needed to make grain to the seeds developing on the plants. The lower amounts of grain harvested from crops grown using CS4 management practices may be due to very low plant growth rates (vegetative vigor) and not a high enough efficiency of using the available resources. The higher productivity of finger millet under advanced natural farming treatments may be attributed to improved nutrient availability, enhanced microbial activity, and better soil physical conditions resulting from the combined application of Beejamrit, Jeevamrit, Ghanajeevamrit, and mulching [11].

Straw Yield (kg ha⁻¹)

Finger millet/barnyard millet straw yields were also significantly influenced by treatment levels. Yields varied widely between years; 2024 yields ranged from the lowest calculation of 971 kg ha⁻¹ for treatment CS3NF2, to the highest calculation of 3,293 kg ha⁻¹ from treatment CS2NF4, while 2025 yielded measurements varied from 1, kg ha⁻¹ for CS1NF1, to 3,161 kg ha⁻¹ for CS4NF4. The highest yields in 2024 occurred from CS2NF4; 3,293 kg ha⁻¹ followed by CS1NF4; 3, kg ha⁻¹, while in 2025 they were also produced by CS4NF4; 3,161 kg ha⁻¹, followed by CS2NF4; 3,048 kg ha⁻¹ and CS3NF4; 3,042 kg ha⁻¹. It was found that all establishment method treatments experienced a gradual increase of straw yield, as applied nutrient levels increased; therefore, the high

straw yield for NF4 treatments was assumed due increased vegetative growth, increased dry matter accumulation and increased nutrient uptake from vegetation thereby producing more total biomass. From these results, it was also suggested that the higher nutrient application level (NF4) can be used to significantly increase both grain and straw yields; of finger millet/barnyard millet. The grain yield from establishment method CS1NF4 proved the highest while the biomass production was greater from establishment methods CS2NF4-C4NF4 compared to treatment CF1NF4 (grains only).

3.2 Lentil/Linseed

Grain Yield (kg ha⁻¹)

Significant influences of agricultural establishment and fertilization regimes occurred with lentil/linseed were observed during both experimental years (2024-25 & 2025-26) (Table 3). In 2024-25, yields ranged from 343 kg ha⁻¹ (CS4NF1) up to 644 kg ha⁻¹ (CS1NF4), while 2025-26 resulted in yields between 204 kg ha⁻¹ (CS2NF1) and 534 kg ha⁻¹ (CS1NF4). The greatest yields among all treatments were noted at CS1NF4. During the year studied, yields amounted to 644 kg ha⁻¹ (2024-25) and 534 kg ha⁻¹ (2025-26). Next, treatment CS3NF4 provided yields of 581 kg ha⁻¹ (2024-25) and 522 kg ha⁻¹ (2025-26) while CS4NF3 yielded 416 kg ha⁻¹ (2024-25) and 525 kg ha⁻¹ (2025-26). Within a particular agro-ecosystem, the relationship between yield and nutrient increases correlated to the fertility classification of the treatment. For example, within CS 1, yield was recorded at 384 kg ha⁻¹ (NF1) and rose to 644 kg ha⁻¹ (NF4). Also within CS2, CS3, and CS4—as nutrient level increased, yield increased. Better quality of yield from treatments NF4 may have occurred due to nutrient availability; root growth; photosynthesis; and the transduction of assimilates sent to reproductive forms. For lentil in particular, increased soil nutrients could enhance plant nodulation and yield due to biological fixation of nitrogen—resulting in increased grains. Increased yield of lentil by treatment NF4 could have arisen from the improvement in soil fertility and microbial growth, which facilitated nutrient mineralization and created favourable rhizospheric conditions for root growth and biological nitrogen fixation [8, 5, 11].

Straw Yield (kg ha⁻¹)

Lentil/linseed straw yields also varied a lot according to how much fertilizer was used or if there was no fertilizer. For example, the highest lentil straw yield (3,407 kg ha⁻¹) occurred in the treatment CS4NF4 during the 2024/25 season, while the lowest occurred in CS1NF1 (2,667 kg ha⁻¹). In the following season (2025/26), the largest straw yield of lentils occurred in CS2NF4 (3,141 kg ha⁻¹), with the smallest straw yield occurring in CS3NF1 (2,454 kg ha⁻¹). During 2024/25, the order of yields for lentils was CS4NF4 (3,407 kg ha⁻¹), CS2NF4 (3,291 kg ha⁻¹) and CS4NF3 (3,178 kg ha⁻¹). In 2025/26, the order of the highest lentil yields was CS2NF4 (3,141 kg ha⁻¹), CS4NF4 (3,028 kg ha⁻¹) and CS2NF1 (2,930 kg ha⁻¹). Overall, as nutrient levels increased across all crop establishment systems, straw yields of lentils would also increase due to the increased availability of nutrients leading to increased vegetative growth, increased dry matter accumulation and increased production of biomass, which resulted in greater amounts of straw yield being produced. Therefore, we can conclude that growing lentil or linseed is more productive at higher levels of fertilization and that in terms of actual numbers, the most productive treatments in terms of grain yield were CS1NF4 and the most productive treatments for straw yield were CS2NF4 and CS4NF4.

Table 1: Available Nitrogen (N), phosphorus (P₂O₅), and potassium (K₂O) status of influenced by cropping systems and natural farming levels in millet-based cropping system

Treatments	N kg ha ⁻¹	P ₂ O ₅ kg ha ⁻¹	K ₂ O kg ha ⁻¹
CROPPING SYSTEMS (M)			
CS1	190	21.4	74.4
CS2	192	21.7	74.6
CS3	191	21.3	74.5
CS4	195	21.8	74.9
S.Em (±)	0.03	0.01	0.16
LSD (P=0.05)	0.09	0.01	NS
NATURAL FARMING LEVELS (S)			
NF1	179	20.1	68.3
NF2	189	21.0	72.5
NF3	199	22.0	76.6
NF4	210	23.1	81.1
S.Em (±)	0.03	0.01	0.08
LSD (P=0.05)	0.10	0.01	0.23
The interactions (M× S) are not significant			

Table 2: Bacteria and fungi count status of soil as influenced by cropping systems and natural farming levels in millet-based cropping system

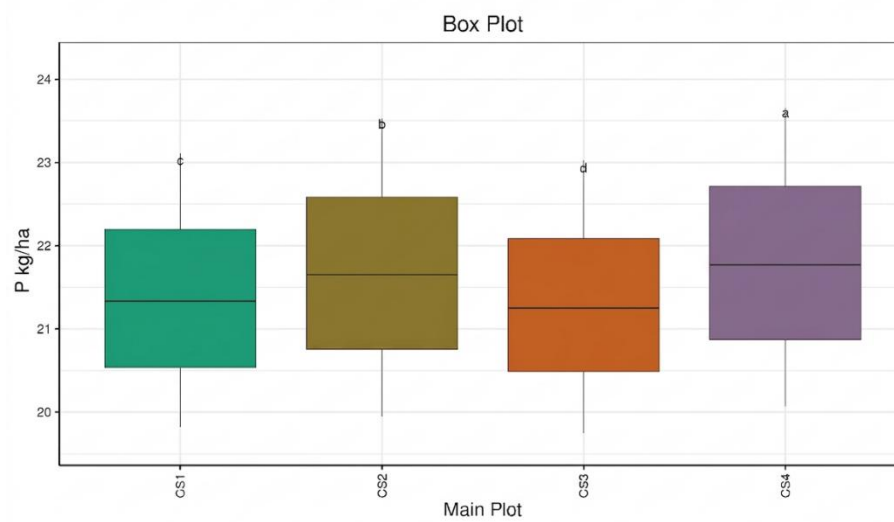
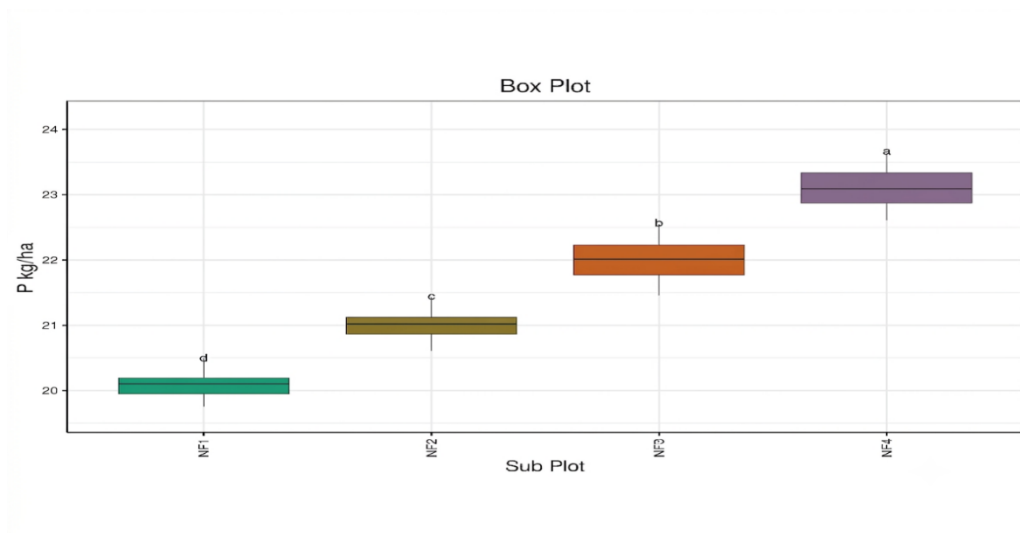
Treatments	Bacterial cfu ×10 ⁷	Fungi cfu×10 ⁵
CROPPING SYSTEMS (M)		

CS1	20.6	10.4
CS2	23.9	11.5
CS3	23.8	11.4
CS4	24.0	11.6
S.Em±	0.03	0.01
C.D @ 5%	NS	NS
NATURAL FARMING LEVELS (S)		
NF1	21.6	10.3
NF2	23.0	11.1
NF3	24.6	11.9
NF4	26.2	12.7
S.Em±	0.02	0.01
LSD (P=0.05)	NS	0.02
The interactions (M× S) are not significant		

Table 3: Grain Yield (kg ha⁻¹) and Straw Yield (kg ha⁻¹) as influenced by cropping systems and natural farming levels in millet-based cropping system

Treatment	Grain Yield (kg ha ⁻¹)		Straw Yield (kg ha ⁻¹)		Grain Yield (kg ha ⁻¹)		Straw Yield (kg ha ⁻¹)	
	Finger millet/ Barnyard millet		Finger millet/ Barnyard millet		Lentil/ Linseed	Lentil/ Linseed	Lentil/ Linseed	Lentil/ Linseed
	2024-25	2025-26	2024-25	2025-26	2024-25	2025-26	2024-25	2025-26
CS ₁ NF ₁	587	443	2358	1984	384	273	2667	2567
CS ₁ NF ₂	848	730	2157	2168	478	366	2834	2720
CS ₁ NF ₃	910	885	2803	2578	581	484	2876	2759
CS ₁ NF ₄	1207	1130	3177	2923	644	534	3000	2873
CS ₂ NF ₁	614	410	2474	2109	356	204	2921	2930
CS ₂ NF ₂	793	689	2273	2293	387	208	2950	2800
CS ₂ NF ₃	940	745	2919	2703	430	294	3062	2826
CS ₂ NF ₄	1165	1090	3293	3048	432	403	3291	3141
CS ₃ NF ₁	383	354	988	2103	426	261	2783	2454
CS ₃ NF ₂	380	430	971	2287	478	354	2950	2607
CS ₃ NF ₃	476	520	993	2697	503	471	2993	2646
CS ₃ NF ₄	670	773	1022	3042	581	522	3117	2760
CS ₄ NF ₁	310	305	983	2222	343	324	3037	2817
CS ₄ NF ₂	436	398	1000	2406	374	433	3066	2687
CS ₄ NF ₃	573	603	1033	2816	416	525	3178	2713
CS ₄ NF ₄	710	810	1005	3161	418	487	3407	3028

Fig. 1: “Impact of cropping systems and natural farming practices on available nitrogen after two years of a millet-based cropping system”



*Refer Table 1 for treatment details**

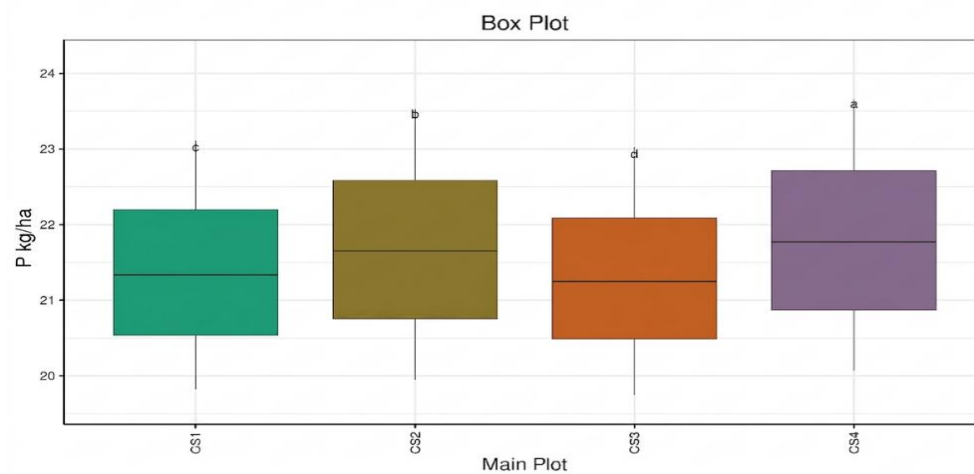


Fig:2 “Impact of cropping systems and natural farming practices on available phosphorus after two years of a millet-based cropping system”

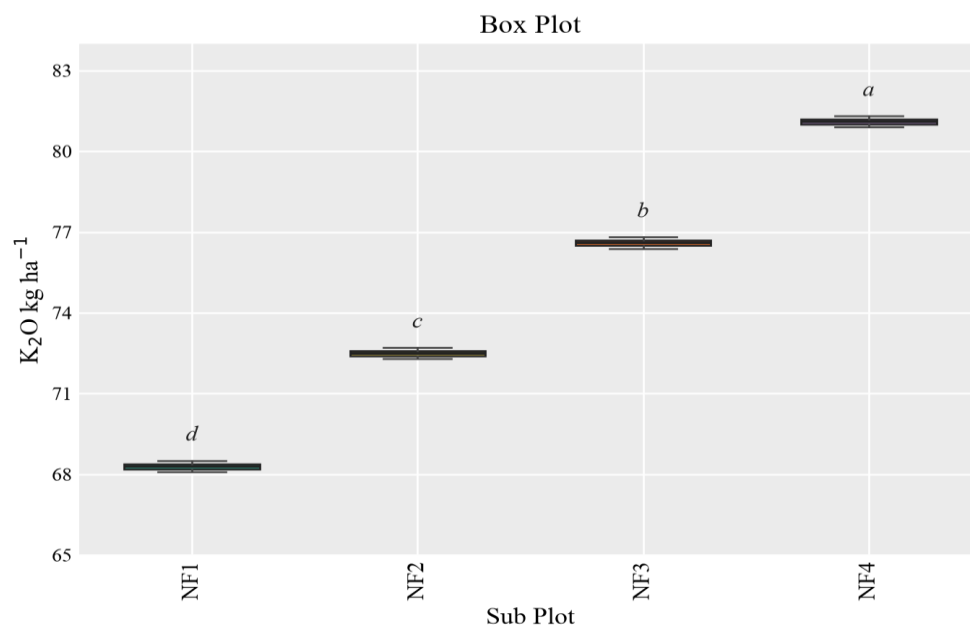
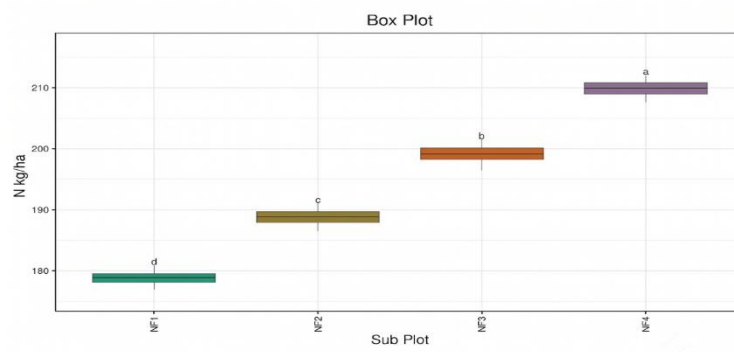
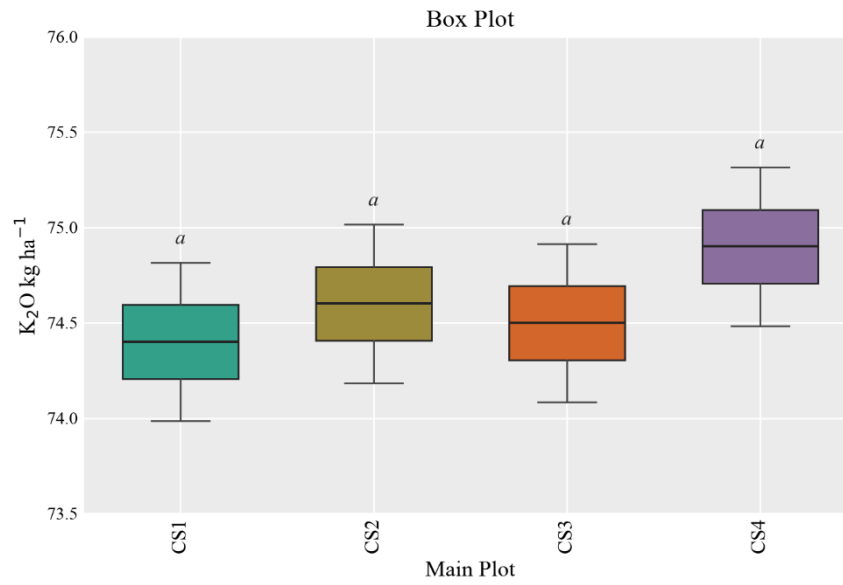


Fig. 3: “Impact of cropping systems and natural farming practices on available potassium after two years of a millet-based cropping system”

*Refer Table 1 for treatment details**

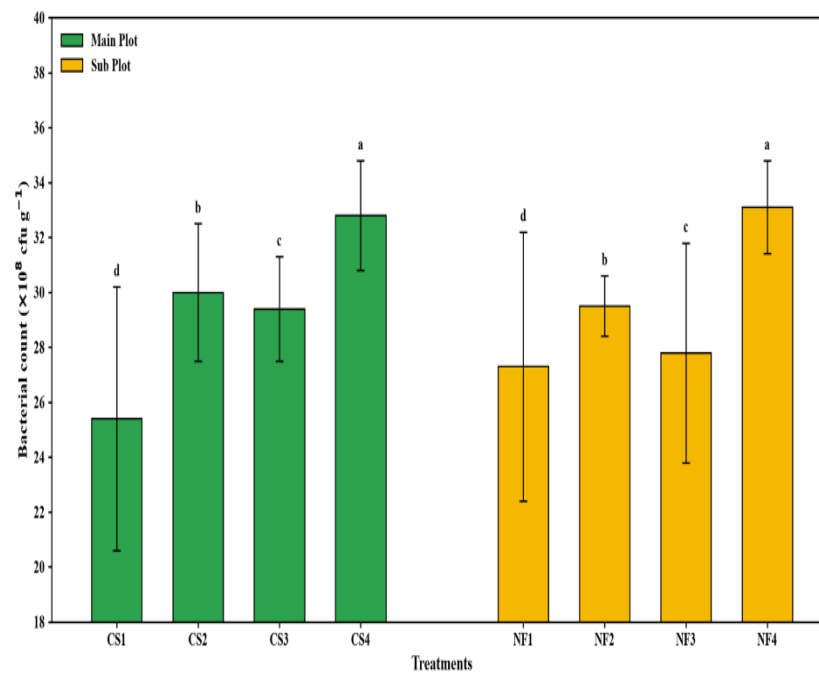
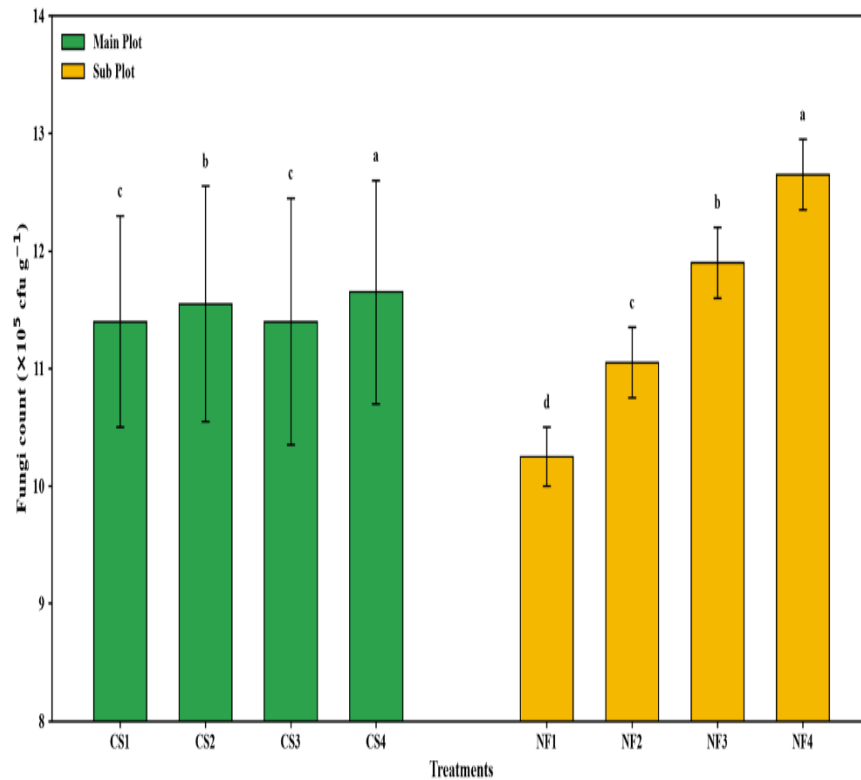


Fig. 4: “Impact of cropping systems and natural farming practices on soil bacterial and fungal population after two years of a millet-based cropping system”

*Refer Table 2 for treatment details**

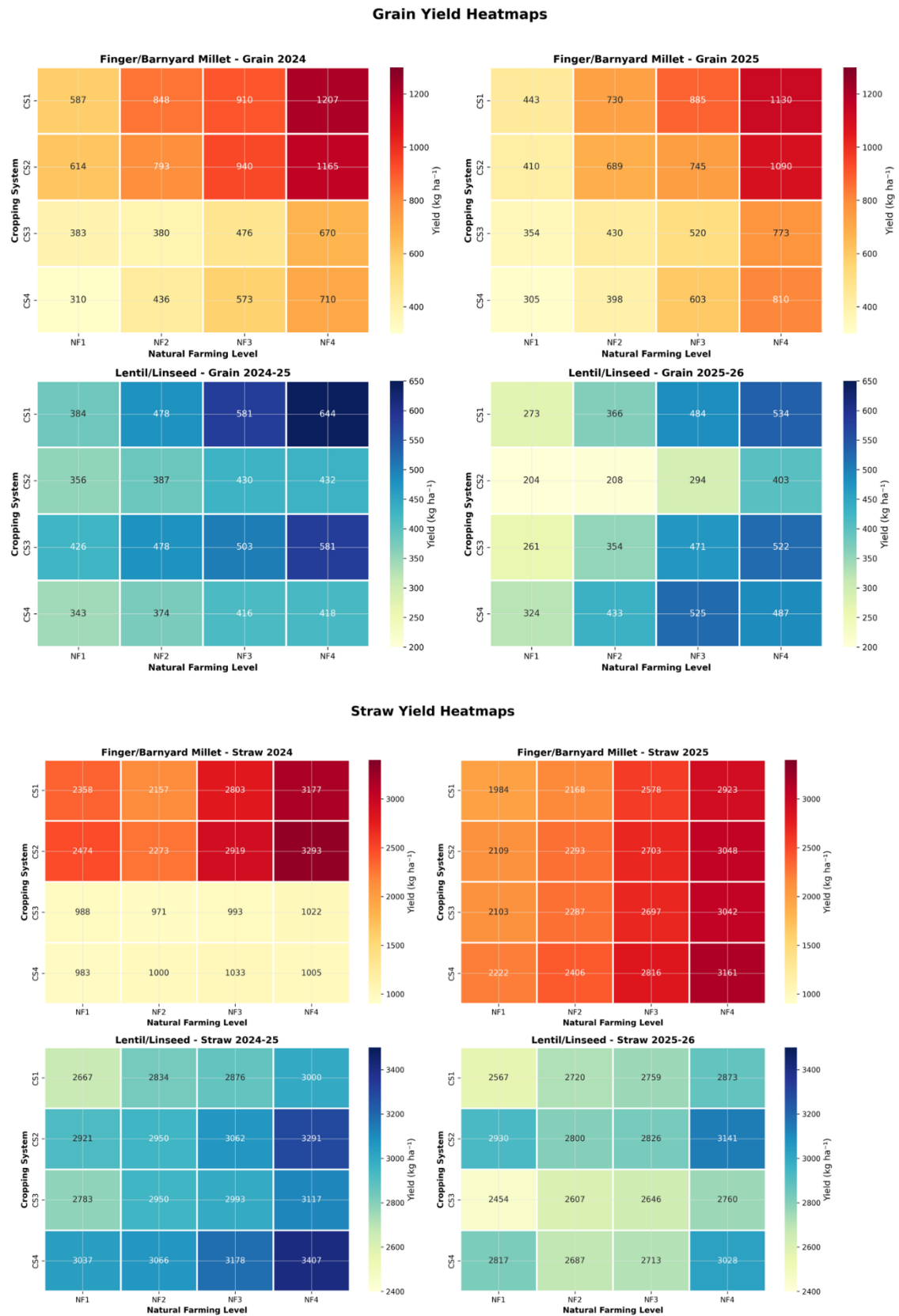


Fig. 5: “Impact of cropping systems and natural farming practices on grain yield and straw yield after two years of a millet-based cropping system”
*Refer Table 3 for treatment details**

CONCLUSION:

The present study demonstrated that the integration of natural farming practices with millet-based cropping systems substantially influenced soil nutrient availability, microbial dynamics, and crop productivity. The findings clearly indicate that biologically driven nutrient management practices enhance soil functioning by stimulating microbial activity and promoting nutrient transformations within the soil-plant system. The superior performance of the NF4 treatment is primarily attributed to its capacity to significantly enhance the soil microbial population. Addressing the potential confounding effect of integrating microbial inoculants (Jeevamrit and Beejamrit) with solid organic amendments and mulching, it is important to emphasize that these components function synergistically. The complete NF4 package acts as a catalyst for microbial proliferation: the inoculants introduce beneficial consortia, while Ghanajeevamrit and organic mulching supply the essential carbon substrates and maintain optimal soil moisture required for their survival and rapid multiplication. Therefore, the substantial improvement in crop productivity and nutrient availability under NF4 is a direct consequence of this elevated microbial population, which accelerates organic matter decomposition and continuous nutrient mineralization.

Among the evaluated cropping systems, the barnyard millet–lentil system (CS4) exhibited superior performance in terms of soil available nitrogen, phosphorus, and potassium, indicating the beneficial effects of crop diversification and millet-legume integration on nutrient cycling and soil fertility. The inclusion of legumes in the cropping sequence likely contributed to improved nutrient turnover, enhanced rhizospheric interactions, and greater biological activity, thereby creating favourable conditions for the maintenance of soil health.

Natural farming treatments exerted a pronounced effect on soil physicochemical and biological properties. The treatment comprising Beejamrit, Jeevamrit, Ghanajeevamrit, and mulching (NF4) consistently recorded the highest values of available nitrogen (210 kg ha⁻¹), available phosphorus (23.1 kg P₂O₅ ha⁻¹), and available potassium (81.1 kg K₂O ha⁻¹), along with maximum bacterial (26.2×10^8 CFU g⁻¹ soil) and fungal populations (12.7×10^5 CFU g⁻¹ soil). These improvements may be attributed to increased organic matter inputs, enhanced decomposition processes, greater substrate availability for soil microorganisms, and improved microbial-mediated nutrient mineralization and solubilization processes.

The study further revealed a positive association between enhanced microbial populations and improved crop productivity, underscoring the fundamental role of soil microorganisms in regulating nutrient availability, particularly nitrogen dynamics, and sustaining crop growth under low-input production systems. The enrichment of bacterial and fungal communities under advanced natural farming practices reflects the development of a biologically active and resilient soil environment capable of supporting long-term ecosystem functioning and productivity.

Overall, the findings of the present investigation establish that the strategic management of soil microbial communities through integrated natural farming practices constitutes an effective approach for improving soil fertility, enhancing nutrient-use efficiency, and sustaining productivity in millet-based cropping systems. The combined application of Beejamrit, Jeevamrit, Ghanajeevamrit, and mulching, particularly when integrated with the barnyard millet–lentil cropping system, emerged as the most promising agroecological strategy for improving soil biological health and nutrient dynamics. Therefore, the adoption of diversified millet-legume cropping systems in conjunction with comprehensive natural farming interventions may be recommended as a sustainable pathway for enhancing soil quality, strengthening microbial-mediated nutrient transformations, and ensuring long-term productivity and resilience of millet-based agroecosystems under resource-constrained conditions.

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