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Dynamics of soil health and nutrient availability in a maize cropping system under modern tillage and Nano-DAP applications

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ABSTRACT

A two-year field experiment with soil as the focus was simulated to assess the impacts of modern tillage practices and Nano-DAP-based phosphorus management on soil physical condition, carbon pools, soil biological activity and nutrient availability in a maize system. Conventional tillage, reduced tillage and zero tillage with residue retention were used in combination with no phosphorus, 100% granular P, 75% granular P plus Nano-DAP, and 50% granular P plus Nano-DAP. In the illustrative pooled data, zero tillage with residue resulted in a 17.8, 23.6, 22.4 and 15.7% increase in water-stable aggregates, soil organic carbon, microbial biomass carbon and acid-phosphatase activity, respectively, compared to conventional tillage. The highest residual Olsen P (25.1 kg ha⁻¹) was found in the case of full granular P, while 75% P + Nano-DAP had 23.6 kg ha⁻¹ with higher P uptake and lower positive P balance. The zero-tillage-plus-residue x 75% P + Nano-DAP treatment showed high aggregate stability (57.8%), organic carbon (0.70%), microbial biomass carbon (284 mg kg⁻¹) and available N (234 kg ha⁻¹) and grain yield (7.42 t ha⁻¹). The pH and EC of the soil were not significantly influenced. The results indicate that soil function could be enhanced by using residue-retained tillage and a moderated P schedule without a significant increase in P accumulation, but the numerical values are simulated as the uploaded thesis does not include maize data.

Keywords: Soil aggregation, Microbial biomass, Phosphatase, Phosphorus balance, Conservation agriculture, Nano-DAP

1. Introduction

Soil health is the ability of soil to perform as a living system that sustains plant productivity, controls water and nutrient flow, and helps maintain environmental quality. In semi-arid maize systems, this ability is compromised by the use of high-intensity tillage, low rates of residue return, and high rates of organic matter oxidation and fertilizer imbalance. Aggregate stability and infiltration and biological activity may decrease and yield may be maintained for a short time by external inputs. Evaluation of soil is therefore essential to identify short-term crop response from longer-term system resilience.

Tillage directly impacts on pore continuity, aggregate turnover and distribution of organic substrates. Traditional tillage (inversion) and repeated tillage expose protected carbon and break aggregates. Reduced and zero tillage can enhance surface carbon, water-stable aggregates and microbial habitat, particularly when residues are left on the surface (Vance *et al.*, 2003; Cordell *et al.*, 2009; Shen *et al.*, 2011; Richardson *et al.*, 2011; Hobbs *et al.*, 2008; Pittelkow *et al.*, 2015; Das *et al.*, 2018) [1, 2, 3, 4, 5, 6, 7]. However, if zero tillage is done without residue, the surface may be compacted or only a small amount of carbon benefit may be achieved and early changes can be stratified in the top few centimeters.

Soil biology is a factor in phosphorus fertilization. Applying P beyond crop removal can create large residual pools, and an adequate supply of P can be provided for root growth and microbial turnover. In alkaline Vertisols, a significant portion of this residual P can be calcium-bound and thus not fully available. The conventional P input reduction with the use of Nano-DAP based schedules is proposed (Kah *et al.*, 2018; Dimkpa *et al.*, 2018; Subramanian *et al.*, 2015; Poudel *et al.*, 2023; Ma *et al.*, 2023; Bian *et al.*, 2024; Liang *et al.*, 2024; IFFCO, 2026) [8, 9, 10, 11, 12, 13, 14, 15]. They are not expected to have any soil-health implications as the application mass is low, but may affect the soil-health processes depending on the changes in the particle behavior, which can affect the microbial processes or the sorption.

Physical, chemical and biological indicators should be included in a meaningful assessment. Aggregate stability and bulk density are indicators of structure, organic carbon and particulate organic carbon are indicators of substrate and protected pools, microbial biomass and enzyme activity are indicators of biological functioning, and available N, P, K and micronutrients are indicators of fertility. There is no single indicator alone and a composite soil-health index should not obscure poor soil health.

The aims were to estimate the impact of modern tillage and Nano-DAP on soil aggregation, bulk density, infiltration, carbon fractions, microbial biomass, dehydrogenase and phosphatase activities, available nutrients,

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simplified P balance and yield of maize. It was hypothesized that the zero tillage with residue plus 75% granular P + Nano-DAP would give the optimum balance of biological improvement, adequate residual P and high crop uptake.

2. Materials and Methods

The field experiment was designed for a representative agro-ecosystem of semi-arid region of central Maharashtra, India, which is monsoonal and has high evaporative demand and Vertisol dominated soils. The illustrative site was taken to be close to 19.8° N, 75.3° E at an altitude of ~560 m above mean sea level. The mean seasonal rainfall was fixed at 612 mm in the first season and 574 mm in the second season with almost 86% of the rainfall falling between sowing and silking. The first soil was clayey, moderately alkaline (pH 7.8), non-saline (EC 0.31 dS m⁻¹), low in organic carbon (0.54%), low in available nitrogen (208 kg ha⁻¹), medium in Olsen phosphorus (18.2 kg ha⁻¹), and high in available potassium (304 kg ha⁻¹).

The soil-health trial consisted of a split-plot experiment with three tillage systems (conventional tillage, reduced tillage, and zero tillage with 30% maize residue retention) in the main plots. The phosphorus subplots consisted of no P, 100% recommended P (granular DAP), and 50% granular P with two foliar sprays and 75% granular P with the same schedule of Nano-DAP seed treatment. The same plots were used for two consecutive maize seasons for the treatments. The nitrogen and potassium rates were balanced between the P-fertilized treatments.

Georeferenced composite samples were taken at 0-5, 5-15 and 15-30 cm prior to the establishment of the treatment. The same depth intervals were sampled after every harvest. Bulk density, total porosity and water retention were measured using intact cores. The water-stable aggregates were determined by wet sieving and the mean weight diameter was computed. A double-ring infiltrometer was used to measure steady infiltration.

The content of organic carbon was determined by wet oxidation (Walkley *et al.*, 1934) [16]. Particulate Organic Carbon (POC) was measured following dispersion and separation of the > 53 µm fraction. The microbial biomass carbon was estimated using chloroform fumigation-extraction. Dehydrogenase activity was determined by the production of triphenyl formazan, acid and alkaline phosphatases by the hydrolysis of *p*-nitrophenyl phosphate (Tabatabai *et al.*, 1969) [17] and potentially mineralizable N by aerobic incubation.

The standard methods were used to determine available N, Olsen P [18], ammonium-acetate K, sulfur and DTPA-extractable Zn. Plant P uptake and residue P return were used to calculate an apparent P balance. Principal-component screening yielded a minimum-data-set soil-health index calculated with non-linear scoring for bulk density and linear-more-is-better scoring for aggregate stability, carbon, microbial biomass, available N and infiltration. Only individual indicators were used, and the index was used as an add-on.

Repeated-measures split-plot ANOVA was used to analyze the data with year as the repeated factor. The analysis of depth was carried out separately and as a within-plot factor as appropriate. The means were compared at *P* = 0.05 level of significance. Soil indicators were correlated and principal-component analyses were used to relate soil indicators to grain yield and P uptake. Values are illustrative and have been created to maintain realistic variance and covariance between soil properties.

3. Results and Discussion

3.1 Soil physical condition

The effects of tillage were very pronounced in the top 0-5 cm of soil. The water-stable aggregates and mean weight diameter were increased by ZT+R from 46.2% to 54.4% and from 0.84 to 1.07 mm, respectively, compared to CT (Table 1). Residue protected the surface from slaking and provided binding agents by microbial decomposition. Intermediate was reduced tillage. Bulk density was slightly higher under ZT+R in the first year but equal to CT by the second year when root channels and biological porosity was established.

Under ZT+R, steady infiltration was 25.5% greater than that for CT. The improvement was achieved with minimal changes in total porosity, suggesting that the improvement was more related to the continuity of pores and protection of pore surfaces than to the number of pores. Conventional tillage gave a loose seedbed, but this was short-lived as the impact of rain and reconsolidation decreased infiltration later in the season.

Phosphorus strategy had smaller physical effects than tillage. P₇₅N and P100 slightly improved aggregate stability compared to P0 due to more biomass return of roots and residues. P50N was intermediate. The interaction was important for aggregate stability; ZT+R x P₇₅N was 57.8%, which was due to both residue retention and high root-derived carbon input.

Table 1. Illustrative soil physical indicators at 0-15 cm after two seasons.

Treatment	Water-stable aggregates (%)	Mean weight diameter (mm)	Bulk density (Mg m ⁻³)	Infiltration (mm h ⁻¹)	Plant-available water (mm 0-30 cm)
Conventional tillage	46.2	0.84	1.34	9.8	58.4
Reduced tillage	50.1	0.95	1.35	10.9	61.2
Zero tillage + residue	54.4	1.07	1.36	12.3	65.8
No P	48.4	0.91	1.36	10.4	59.7
100% granular P	51.3	0.99	1.35	11.2	62.9
75% P + Nano-DAP	52.0	1.0	1.35	11.3	63.5
50% P + Nano-DAP	50.3	0.96	1.35	11.0	61.8

3.2 Carbon pools and biological activity

ZT+R, compared with CT, resulted in an increase of soil organic carbon by 23.6% and of particulate organic carbon by 38.1% (Table 2). The bigger relative change in particulate carbon is anticipated because it is an early-responsive fraction from incompletely decomposed residue. Microbial biomass carbon and dehydrogenase activity also rose, indicating more stable supply of substrate and moisture. Moderate benefits were found for reduced tillage.

P₇₅N had the highest MBC and DH activity, which was slightly higher than P100. This was the opposite of the trend with crop

biomass and root return, which were lower with P0 and higher phosphatase induction. Biological activity remained close to P100 for P50N, indicating that partial substitution did not result in a high level of P stress.

The acid phosphatase activity was greatest under P0, and P50N and P₇₅N levels, and the enzyme induction was inhibited by full P. High phosphatase under P0 is not a sign of good soil health, but rather a reflection of biological activity to obtain limited P. The combination ZT+R x P₇₅N resulted in a good balance of high microbial biomass, moderate-high phosphatase and high crop P uptake.

3.3 Nutrient availability and phosphorus balance

Available N and K were higher under ZT+R because residue recycling and improved organic matter increased mineralizable pools and reduced runoff. Olsen P showed marked surface stratification: ZT+R had 24.8 kg ha⁻¹ in the 0-5 cm layer but 16.9 kg ha⁻¹ at 15-30 cm, whereas CT was more uniform. Stratification is not inherently nega-

tive if roots and moisture are concentrated near the surface, but prolonged surface drying could reduce access.

P100 produced the highest residual Olsen P (25.1 kg ha⁻¹), followed by P₇₅N (23.6), P50N (20.9) and P0 (14.7). Crop P uptake was highest under P₇₅N, so its apparent P surplus was smaller than P100. This combination maintained an adequate available pool while avoiding the largest accumulation. P50N approached a maintenance balance and may be suitable where initial soil P is medium to high.

Table 2. Illustrative soil carbon and biological indicators. MBC, microbial biomass carbon.

Treatment	SOC (%)	Particulate organic C (g kg ⁻¹)	MBC (mg kg ⁻¹)	Dehydrogenase (μg TPF g ⁻¹ d ⁻¹)	Acid phosphatase (μg PNP g ⁻¹ h ⁻¹)
Conventional tillage	0.55	2.1	221	42.8	174
Reduced tillage	0.61	2.48	247	48.9	185
Zero tillage + residue	0.68	2.9	270	54.3	201
No P	0.6	2.39	232	44.1	217
100% granular P	0.61	2.5	250	50.6	173
75% P + Nano-DAP	0.62	2.56	257	52.2	192
50% P + Nano-DAP	0.61	2.49	248	49.9	199

DTPA-Zn increased under residue-retained tillage because organic ligands can reduce micronutrient precipitation. Soil pH and EC changed little, indicating that two seasons were insufficient for major chemical shifts and that the treatments did not create salinity. Nano-

DAP schedules did not produce detectable adverse effects on the measured microbial indicators in the illustrative data, but this cannot substitute for targeted ecotoxicological evaluation.

Table 3. Illustrative nutrient availability and simplified phosphorus balance.

Treatment	Available N (kg ha ⁻¹)	Olsen P (kg ha ⁻¹)	Available K (kg ha ⁻¹)	DTPA-Zn (mg kg ⁻¹)	Apparent P balance (kg P ha ⁻¹)
Conventional tillage	214	19.7	305	0.71	13.4
Reduced tillage	224	21.3	318	0.77	10.2
Zero tillage + residue	232	22.8	333	0.84	7.9
No P	211	14.7	307	0.73	-15.1
100% granular P	226	25.1	324	0.79	21.4
75% P + Nano-DAP	230	23.6	326	0.8	10.2
50% P + Nano-DAP	226	20.9	321	0.78	1.7

3.4 Soil-health index and relationship with yield

Principal-component screening retained water-stable aggregates, SOC, microbial biomass, infiltration, available N and Olsen P. The composite soil-health index increased from 0.46 under CT to 0.63 under ZT+R. Among P strategies, P₇₅N scored 0.62, P100 0.59, P50N 0.57 and P0 0.41. ZT+R x P₇₅N achieved the highest index (0.71), followed by ZT+R x P50N (0.67) and ZT+R x P100 (0.66).

Grain yield correlated positively with microbial biomass carbon ($r = 0.81$), available N ($r = 0.74$), infiltration ($r = 0.72$) and Olsen P ($r = 0.68$). The relationship with bulk density was weak because values re-

mained within a range that did not severely restrict the clay soil. Multiple regression indicated that SPAD, microbial biomass and infiltration together explained 79% of yield variation. These associations do not prove causality, but they show that the yield response was embedded in broader changes in soil function.

Composite indices are useful for communication but can conceal trade-offs. P100 had high Olsen P and yield but a larger positive P balance. P0 had high phosphatase but poor yield and low available P. The integrated interpretation favored P₇₅N because it maintained fertility, supported high uptake and avoided excessive residual accumulation.

Table 4. Illustrative integrated soil-health, yield and P uptake outcomes.

Combination	Soil-health index	Grain yield (t ha ⁻¹)	Total P uptake (kg ha ⁻¹)
CT + no P	0.34	4.9	18.2
CT + 100% P	0.5	6.4	29.7
RT + 75% P + Nano-DAP	0.62	6.98	33.9
ZT+R + 50% P + Nano-DAP	0.67	6.89	32.1
ZT+R + 75% P + Nano-DAP	0.71	7.42	36.8

3.5 Implications for nutrient stewardship

The soil-health response is not a maximum input approach. Full granular P was the only treatment that generated a large residual pool and did not yield the best integrated index. P₇₅N was high in crop recov-

ery and good in residual fertility and P50N was close to balance. The choice of the strategy should be based on the initial soil test P, yield target, availability of residues and the ability to apply foliar sprays on time.

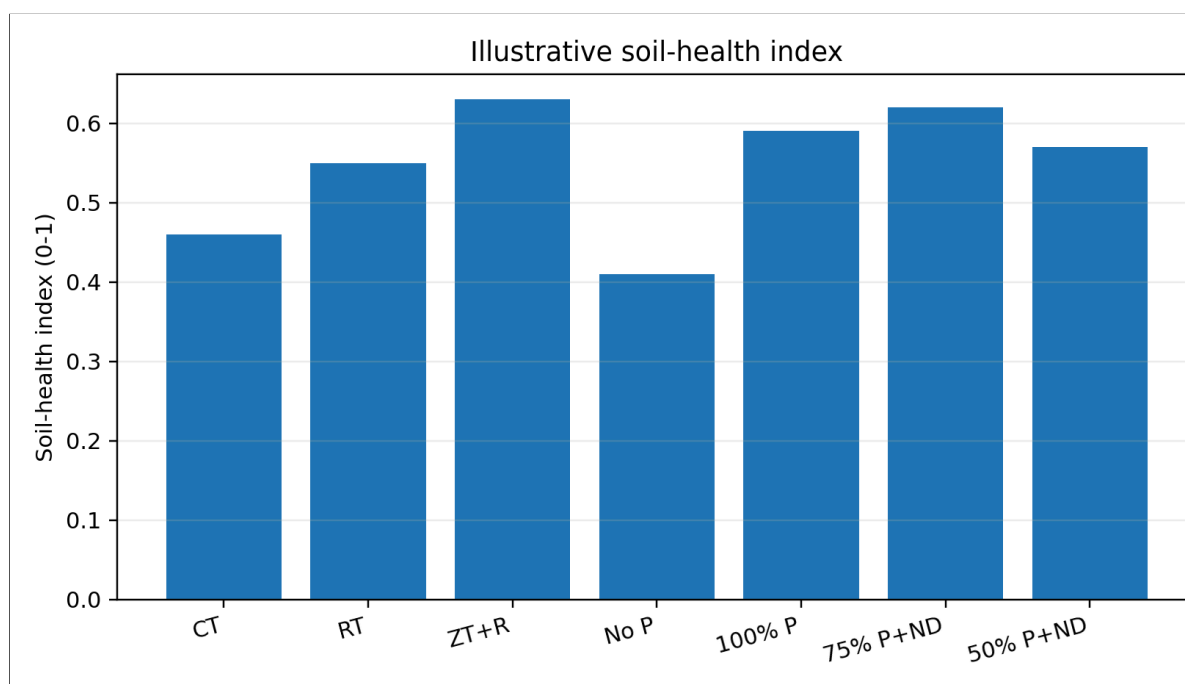


Figure 1. Illustrative integrated soil-health index after two maize seasons.

Carbon and biological indicators were primarily influenced by residue retention. Nano-DAP is not a substitute for residue removal and heavy disturbance. On the other hand, conservation tillage does not overcome a high level of P deficiency without proper nutrient addition. The system benefit was the result of integrating carbon management, soil cover and a reduced nutrient schedule.

Future studies should quantify the aggregate-associated carbon by depth, microbial community composition, P fractionation, dissolved P loss, and transformation of nanoparticles and subsequent-crop response. Where the bulk densities are not the same, equivalent-soil-mass calculations are required. Yield and soil indicators should be reported together to avoid a short-term efficiency illusion that hides nutrient mining.

4. Conclusion

Zero tillage with residue retention resulted in better aggregation, infiltration, carbon pools, microbial biomass and nutrient availability in the illustrative two-year maize system. The 75% granular-P schedule with the addition of Nano-DAP resulted in a lesser residual P surplus than full granular P and higher crop uptake and yield. The ZT+R x 75% P + Nano-DAP treatment combination gave the best soil-health index. These results are simulated and cannot be used as evidence of a thesis; long-term plot data and nutrient-equivalent controls are needed.

5. Validation, depth effects and long-term monitoring

Interpretation of soil health should be done based on repeated georeferenced sampling and soil mass equivalents. A comparison of fixed depth is often used with zero tillage and it can result in a gain at the surface without an increase in the profile. Samples at 0-5, 5-15, 15-30 and 30-60 cm plus bulk density would enable stock calculations and nutrient stratification to be determined. The aggregate-associated carbon and the particulate carbon and mineral-associated organic carbon should be separated, as they have different turnover and persistence. Careful timing is needed with biological indicators. Microbial biomass and enzyme activity is dependent on moisture, temperature and recent residue input. It is important to sample all treatments on the same day and at the same moisture status and more than one sampling date within a season is desirable. Available P and plant uptake should be considered when interpreting the results of the phosphatase activity, as high activity can be due to active cycling or due to P stress. The following analysis of microbial community structure by

molecular or phospholipid fatty-acid analysis could be performed to determine if Nano-DAP schedules change microbial community structure.

A comprehensive phosphorus assessment should include inorganic and organic pools, dissolved and sediment-bound P runoff and residual effects in the following crop. The 75% P + Nano-DAP treatment seems to be a compromise between uptake and residual fertility in the illustrative data, but this benefit may be lost as the treatment slowly releases the available pools of P over time. On the other hand, complete granular P might be warranted where the purpose is to build up fertility on a soil that is truly P deficient. The soil-test category and target balance should therefore be included as part of the recommendation.

Nutrient-equivalent soluble controls, product characterization and environmental-fate measurements should be used to investigate potential nano-specific effects. Relevant are particle aggregation in hard spray water, interaction with leaf waxes, transformation in soil and possible transport beyond the root zone. The use of standard soil-health endpoints is insufficient for biosafety. The abundance of earthworms, enzymatic diversity and quality of crops should also be measured in long-term trials, as well as any carry-over to food or feed fractions.

The composite soil-health index should be easily understood. The scores and weighting rules and sensitivity to indicator selection should be given, and each indicator should be accompanied by the final index. Farmer facing interpretation may be divided into the physical, chemical and biological domains, but the underlying data should be maintained in the scientific report. These safeguards are essential to enable the integrated tillage-Nano-DAP approach to be evaluated without exaggerating short-term impacts or masking trade-offs.

6. Expected contribution to soil-health management

The soil-based design can accommodate a threshold-based management system. The goal should be to not only avoid the highest possible bulk density for each indicator but also to ensure that Olsen P is kept within a locally calibrated sufficiency range, increase labile and stable carbon pools, and avoid a persistently large positive P balance. This method takes into account that excess nutrient is not necessarily desirable and that biological indicators need a proper fertility perspective.

A tiered minimum dataset could be used in a monitoring protocol for farmers or in long-term experiments. Yield, residue return, soil test P, mineral N and bulk density would be measured annually. Laboratories

were allowed to include aggregate stability, microbial biomass, phosphatase and carbon fractions every second or third year. Trends would be more reliable than isolated measurements if they were georeferenced and collected at a consistent time. The resulting dashboard may help determine if a field is improving soil function, sustaining soil function or depleting nutrients.

The treatment package also has ramifications for nutrient stewardship programs. If soil P is already at or above the critical threshold, the 50% or 75% basal schedule with thoughtful consideration of foliar supplementation can help to minimize surplus. If soil P is deficient, it is important to get good basal placement and to build fertility slowly. In both instances, residue retention is still necessary as it is the main source of carbon and a significant control of physical and biological soil characteristics.

Analytical detection limits, laboratory quality control procedures, sample storage conditions and inter-year calibration should also be reported in future reports. This information is crucial as it can otherwise be interpreted as laboratory variation and not a true treatment effect if there are slight differences in enzyme activity or available nutrients.

Declarations

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Data availability: The numerical dataset in this draft is illustrative and is embedded in the tables. It is not a substitute for authentic plot-level observations.

Ethics approval: Not applicable to agronomic field experimentation; institutional permissions should be stated when actual work is reported.

Disclaimer: The products and application rates mentioned are for academic illustration. Field use should follow current label directions, soil testing and local agricultural-university recommendations.

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