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BRIDGING SOIL FERTILITY AND YIELD: THE IMPACT OF COMBINED ORGANIC MANURES AND INORGANIC FERTILIZERS ON AGRO-ECOSYSTEMS

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Abstract

Sustained productivity of intensive cropping systems is dependent on maintaining soil fertility, but when inorganic fertilizers are used, they can increase yield but tend to decrease the levels of soil organic matter and cause degradation of the biological and physical properties of the soil, which on the other hand, when used as organic manures or biofertilizers can improve the properties of soil, but cannot provide enough nutrients to meet the needs of high yields. Integrated nutrient management integrates inorganic fertilizer with organic manure and biofertilizer, aiming to combine the nutrient supply of the inorganic component with the soil improving properties of the organic and biological components. The impact of integrated nutrient management on the productivity of the crops, soil microbial biomass and physicochemical properties of soil was assessed in this 2 seasons field study. An unfertilized control, full inorganic fertilizer, farmyard manure alone, biofertilizer alone and three integrated nutrient management treatments, which culminated in full integrated nutrient management, were tested in a randomized complete block design with four replications in two seasons. The highest integrated nutrient management gave the best results in terms of grain yield (5.3 t ha $^{-1}$) compared with inorganic fertilizer alone (4.4 t ha $^{-1}$) and control (no fertilizer applied, 2.9 t ha $^{-1}$) and also resulted in the greatest soil microbial biomass carbon, soil organic carbon, available nutrients, water-holding capacity, and the least bulk density. The grain yield was strongly and positively associated with soil microbial biomass carbon. The results showed that the use of integrated nutrient management (IMn) which is the combination of organic manure, inorganic fertilizer and biofertilizer was found to increase the productivity of the crops higher than that of using inorganic fertilizer alone and the physicochemical properties and microbial activity of the soil were also improved, thus providing a sustainable alternative to inorganic fertilizer.

Keywords: *integrated nutrient management; organic manure; biofertilizer; crop productivity; soil microbial biomass; soil organic carbon; soil physical properties; sustainable agriculture*

INTRODUCTION

The viability of the intensive cropping systems on which the food security of a burgeoning population is dependent is ultimately based on soil fertility, and maintenance of soil fertility is one of the central issues in agriculture. The impact of the

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introduction of chemical fertilizers into agriculture over the past century has been marked by the huge increase in crop yields, and their use has proven essential to feeding the world, particularly for the removal of nitrogens, phosphors and potash from soils. However, the use of inorganic fertilizer alone for several years has shown its limitations and increase in costs; production and application of inorganic fertilizer require energy, while carbon is required for organic matter in the soil, which is lost; the production and use of inorganic fertilizer cause losses of nutrients to water and to the air and leads to a reduction in the biological and physical properties of the soil [2,3].

By contrast, organic sources of nutrients have complementary strengths and weaknesses: the manures and composts that were the essential nutrients before the development of chemical fertilizer. Organic manures provide nutrients in a slow-release manner as they decompose, and also add organic carbon to the soil, nourish the microbial population and enhance soil structure and ability to hold water, thus sustaining and enhancing biological and physical health of the soil which inorganic fertilizer does not. However, they are unable to provide the high levels of nutrients needed by high yielding crops in the amounts available in practice, due to low nutrient content and slow nutrient release; so organic manure alone is not sufficient to achieve high yields. The biofertilizers (preparation of beneficial micro-organisms for nitrogen fixation, phosphorus solubilization, or plant growth) introduce another level and further complement the biological nutrient supply and plant growth processes, but are similarly unable to provide the complete nutrient requirement [5].

As a result of the recognition of these complementary strengths and limitations, the concept of integrated nutrient management has emerged, which involves integrated use of inorganic, organic and biological sources of nutrients to bring together their strengths and offset their weaknesses [6]. It is based on the idea that the inorganic fertilizer provides the large and immediate nutrient requirement of plants, that the organic fertilizer replenishes the organic matter lost during the cultivation, and that the biofertilizer adds to the biological and physical fertility lost by using inorganic fertilizer, thereby providing a better productivity and sustainability than any of the sources alone. Integrated nutrient management has therefore emerged as a major approach in managing soil fertility sustainably and significant research on the impacts of INM on crop yield and soil characteristics in cropping systems has been developed [7].

Evaluation of integrated nutrient management must take into account the impact of integrated nutrient management on the productivity of the crop as the short-term agronomic outcome, but also the impact on the properties of the soil that determine its longer-term health and fertility, namely the soil organic carbon and the available nutrients, as chemical measures of fertility; the microbial biomass and activity, as biological measures and which reflect and drive the cycling of nutrients and the building of organic matter; and the physical properties, such as the bulk density and the water holding capacity, which determine the structure of the soil and its capacity to store water and to support roots. Soil microbial biomass, in particular, is an early and sensitive measure of the impact of management on soil health, and has a much quicker response to changes in soil health than the more slowly changing soil organic carbon, reflecting the biological vitality of the soil [8]. The aim of this study was to assess how this can be achieved through an integrated nutrient management. To compare the productivity of the crop and the soil microbial biomass in the integrated nutrient management with inorganic fertilizer alone, organic manure alone and biofertilizer alone and to test the relationship between soil microbial biomass and crop productivity.

2. Literature Review

The constraints of inorganic fertilizer alone on which integrated nutrient management is based, have been well documented from long term experiments. The long-term application of inorganic fertilizer alone over decades has been shown to lead to a decrease in soil organic carbon, soil microbial biomass and activity, and soil structure compared to systems that include addition of organic inputs, [2,3,9]. The

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environmental price of the intensive application of fertilizer nitrogen (the loss thereof to water and atmosphere) has been described, thus contributing to the arguments for the use of organic and biological sources [10]. This literature defines the problem to be solved by integrated nutrient management.

The advantages of using organic manures, and the complementarity between organic manures and inorganic fertilizer, has been shown. Organic manures have been demonstrated to increase soil organic carbon, microbial biomass and activity, soil structure and water holding capacity, provide nutrients in a slow release manner, and biofertilizers increase biological N fixation and solubility of P and plant growth promotion [4,5,11]. The combination has been justified because of the complementarity of the sources (inorganic source to meet the immediate nutrient requirement, organic source to build the soil, and the biological source to enhance the biological processes) [6]. This body of work sets out the strengths of the individual sources and on the basis of this the foundation for the integration of these is laid.

The effects of integrated nutrient management on crop yield and soil properties have been examined in many studies and syntheses. Research has clearly shown that yields obtained from INM are not inferior and are equivalent or superior to those of inorganic fertilizer alone, and that the soil organic carbon, microbial biomass and activity, available nutrients and soil physical properties are superior compared to those of inorganic fertilizer alone [7,12]. The long-term experiments have been most useful in terms of the long-term benefit of integration on both yield and soil health [9]. This evidence is gathered by the syntheses of integrated nutrient management and integrated soil-fertility management, resulting in the approach being regarded as one of the main strategies of sustainable soil-fertility management [6,13]. This literature has set the general benefit of integrated nutrient management.

An important theme that becomes apparent in this literature and becomes the focus of the present study is the fact that the importance of an integrated nutrient management system is not only in the yield produced but also in the soil health which may not be achieved by inorganic fertilizer alone. Evaluation of IM is therefore required to be done in tandem, with both productivity and soil-health outcomes taken into account, otherwise it will be underinvested by only considering productivity and discounting the key benefit of IM, which is the creation of biological and physical soil fertility that will be lost if inorganic fertilizer is used. Of particular importance in this assessment are the soil microbial biomass, as it is a sensitive, early indicator of soil-health change; it is an indicator of the biological improvement under integration before the slowly-changing SOC does. [8,14] This principle – that both productivity and soil health must be measured – drove the design of the current study, which measured both productivity and soil health.

The relationship between the soil microbial biomass and crop productivity, which the present study examines, has been explored and provides a link between the biological health of the soil and its agronomic output. Under land use which builds both microbial biomass and crop yield, the two are often correlated with larger and more active microbial biomass being linked to a higher nutrient supply and higher crop yield [8,14]. This relationship between the biological improvement achieved under INM and its productivity has been demonstrated, thus contributing to the use of the microbial biomass as an indicator of the agronomic and biological improvement. The present study is a combined evaluation of the productivity, microbial-biomass and physico-chemical effects of integrated nutrient management and testing of the microbial-biomass–yield relationship.

3. Methodology

The trial was carried out as a field experiment in two successive growing seasons at a typical location in the intensive cereal-cropping area. The experiment was laid out in Randomized complete block design (RCBD) with four replicate blocks. The treatments included three different nutrient-management systems: unfertilized control, full inorganic fertilizer (75% of the recommended N, P, K levels) and farmyard manure, biofertilizer alone, and 75% of the recommended inorganic

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fertilizer supply with farmyard manure, 50% of the recommended inorganic fertilizer supply with farmyard manure and biofertilizer, and full inorganic fertilizer supply with farmyard manure and biofertilizer (full integrated nutrient management). The treatments aimed to compare the individual sources, the integrated combinations and the control and to evaluate the effect of integration against the inorganic source and the organic and biological source.

Farmyard manure was applied at a known rate and ploughed in prior to sowing and the nutrient content determined so that total nutrient inputs of the treatments could be accounted for. Biofertilizer was a formulation of beneficial microorganisms suitable for the crop, and was applied in the usual manner. To represent the crops grown in the region, a single cereal crop was sown at the recommended crop density and managed according to the normal practice, being irrigated and subjecting the crop to uniform treatment of weeds and pests, except for the way in which the crops were being fertilized.

The soil microbial biomass C, which acts as a biological indicator of soil health, was measured using a standard method in each plot before and after each season of the experiment and the physicochemical properties – organic C, pH, available N, P and K, bulk density and water-holding capacity – were also determined. The nutrient uptake by the plant was calculated from the nutrient content and the biomass of the crop; the growth of the crop throughout the season was monitored. The yield components and the grain yield were determined in harvested plots at maturity.

Data were analyzed by analysis of variance, where significant differences were detected at 0.05 probability level, the treatment means were compared using the least significant difference, and the season was considered. To assess the association between the microbial biomass carbon of soil and grain yield under various treatments and replications, correlation and regression was conducted. All data were analyzed using conventional statistical methods and differences were accepted as significant at the 0.05 level.

4. Results

The experimental design of the study and the workflow along the study is summarized in Figure 1. The nutrient management affected the grain yield in a significant and strong way, with unfertilized control yielding 2.9 t ha−1, inorganic fertilizer alone 4.4 t ha−1, the organic and biological treatments alone intermediate yields of 3.6 and 3.2 t ha−1 respectively, and the integrated nutrient management treatments produced the highest yields, reaching 5.3 t ha−1 under full integrated nutrient management, which was significantly higher than that of inorganic fertilizer alone. The agronomic benefit of integration was thus demonstrated since the integrated organic and biological sources with the inorganic fertilizer led to a higher yield than could be obtained by using the inorganic fertilizer alone.

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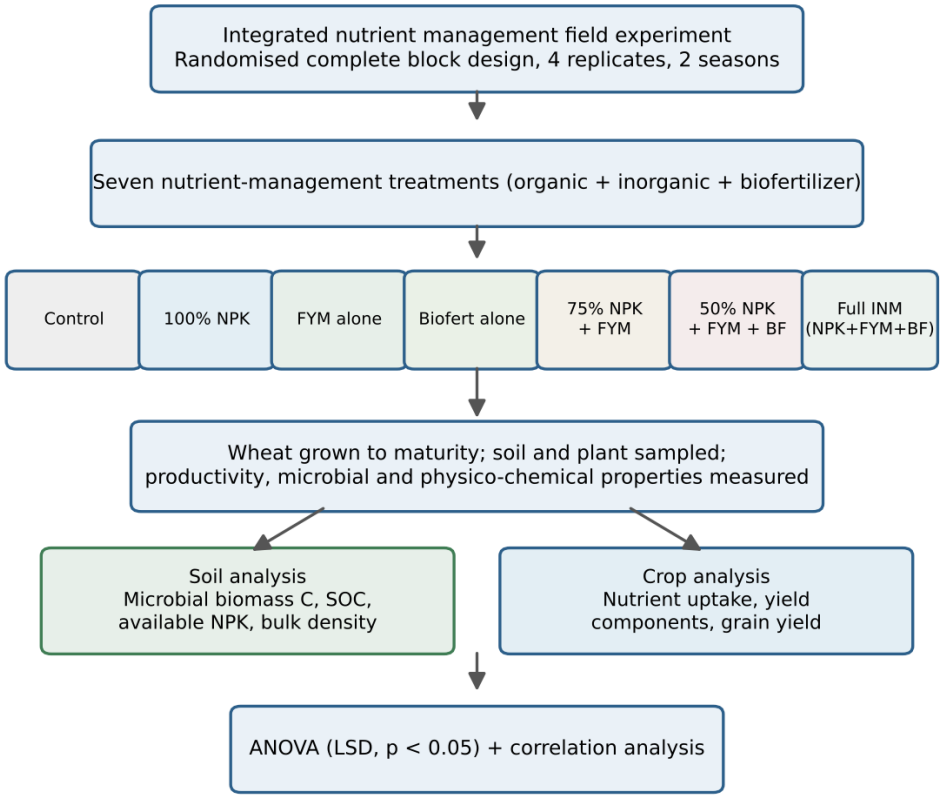

Figure 1. Experimental design and workflow: seven nutrient-management treatments in a randomised complete block design over two seasons, with productivity, microbial, and physico-chemical analysis.

Table 1. Grain yield, yield components, and nutrient uptake by treatment (means over two seasons).

Treatment	Grain yield (t ha^{-1})	Tillers (m^{-2})	1000-grain wt (g)	N uptake (kg ha^{-1})
Control	2.9	241	36.1	52
100% NPK	4.4	318	40.8	98
FYM alone	3.6	284	38.9	78
Biofertilizer alone	3.2	266	37.8	70
75% NPK + FYM	4.9	352	42.4	124
50% NPK + FYM + BF	4.6	339	41.6	118
Full INM	5.3	378	43.6	138

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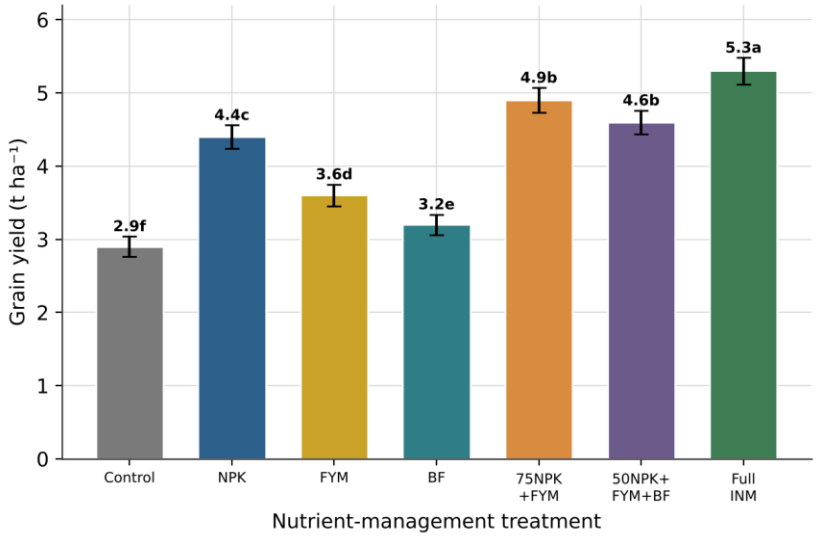

Figure 2. Grain yield by nutrient-management treatment (means over two seasons with standard-error bars). Bars sharing a letter do not differ significantly (LSD, $p < 0.05$).

The soil microbial biomass carbon, the biological indicator of soil health, responded to the nutrient management in a pattern that, importantly, differed from that of yield, as shown in Figure 3. The microbial biomass was lowest in the control and, notably, was raised only modestly by inorganic fertilizer alone, to 186 mg kg^{-1}, but was raised markedly by the treatments containing organic manure, reaching 356 mg kg^{-1} under full integrated nutrient management, with farmyard manure alone giving a higher microbial biomass than inorganic fertilizer alone despite its lower yield. This divergence — the microbial biomass responding to the organic rather than principally to the inorganic inputs — reveals the distinct effect of the organic component on the biological health of the soil, which inorganic fertilizer alone does not provide and which is the principal soil-health benefit of integration.

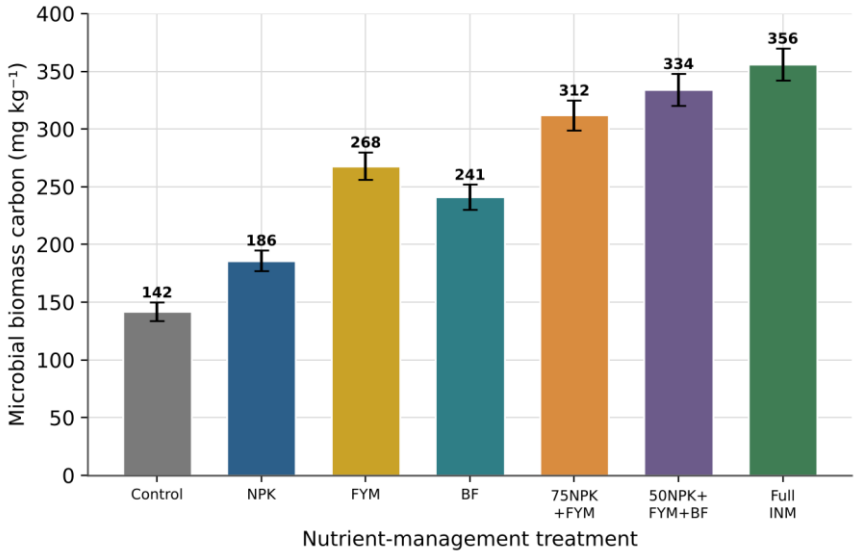

Figure 3. Soil microbial biomass carbon by treatment (means with standard-error bars). The organic-containing treatments raised microbial biomass far more than inorganic fertilizer alone.

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The soil chemical properties followed a pattern consistent with the inputs, as shown in Figure 4 and reported in Table 2. The soil organic carbon was raised by the organic-containing treatments but little by inorganic fertilizer alone, reaching 8.9 g kg^{-1} under full integrated nutrient management against 6.0 g kg^{-1} under inorganic fertilizer alone and 5.8 in the control, reflecting the return of organic matter by the manure; while the available nitrogen was highest under the integrated treatments, reflecting both the inorganic supply and the mineralization of the organic input. The contrast between the soil organic carbon under the organic-containing treatments and under inorganic fertilizer alone reproduces, at the level of this two-season study, the depletion of soil organic carbon under inorganic fertilizer alone that the long-term experiments reveal, and demonstrates the building of soil organic carbon by the integration of organic inputs.

Table 2. Soil physico-chemical and biological properties after two seasons by treatment (means).

Treatment	SOC (g kg^{-1})	Avail. N (mg kg^{-1})	MBC (mg kg^{-1})	Bulk density (g cm^{-3})	WHC (%)
Control	5.8	42	142	1.52	32
100% NPK	6.0	68	186	1.50	33
FYM alone	7.6	61	268	1.41	41
Biofertilizer alone	6.9	58	241	1.46	38
75% NPK + FYM	8.2	86	312	1.38	44
50% NPK + FYM + BF	8.4	82	334	1.36	45
Full INM	8.9	94	356	1.34	47

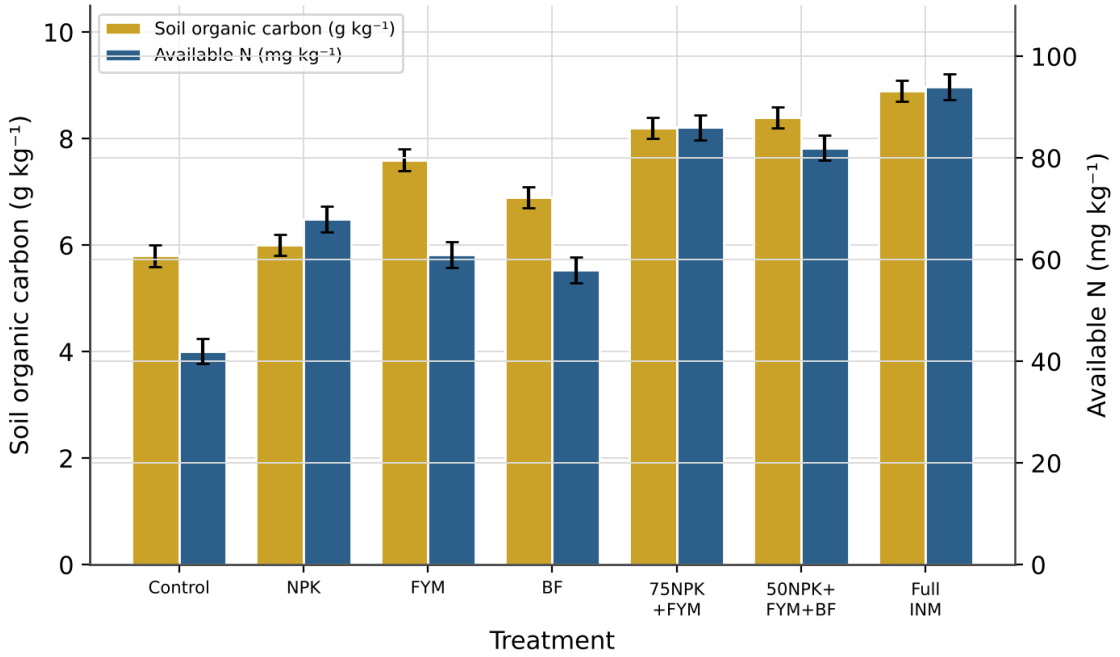

Figure 4. Soil organic carbon and available nitrogen by treatment (means with standard-error bars). The organic-containing treatments raised soil organic carbon; the integrated treatments raised available nitrogen most.

The soil physical properties improved markedly under the organic-containing treatments, as shown in Figure 5. The bulk density, a measure of soil compaction that is lower in well-structured

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soils, fell from 1.52 g cm^{-3} in the control to 1.34 g cm^{-3} under full integrated nutrient management, and the water-holding capacity rose from 32% to 47%, reflecting the improvement in soil structure that the organic matter conferred. Inorganic fertilizer alone, by contrast, improved these physical properties little, consistent with its lack of effect on soil organic matter. These improvements in the physical properties, like those in the microbial biomass and the soil organic carbon, were conferred by the organic component of the integrated treatments and are the physical dimension of the soil-health benefit of integration.

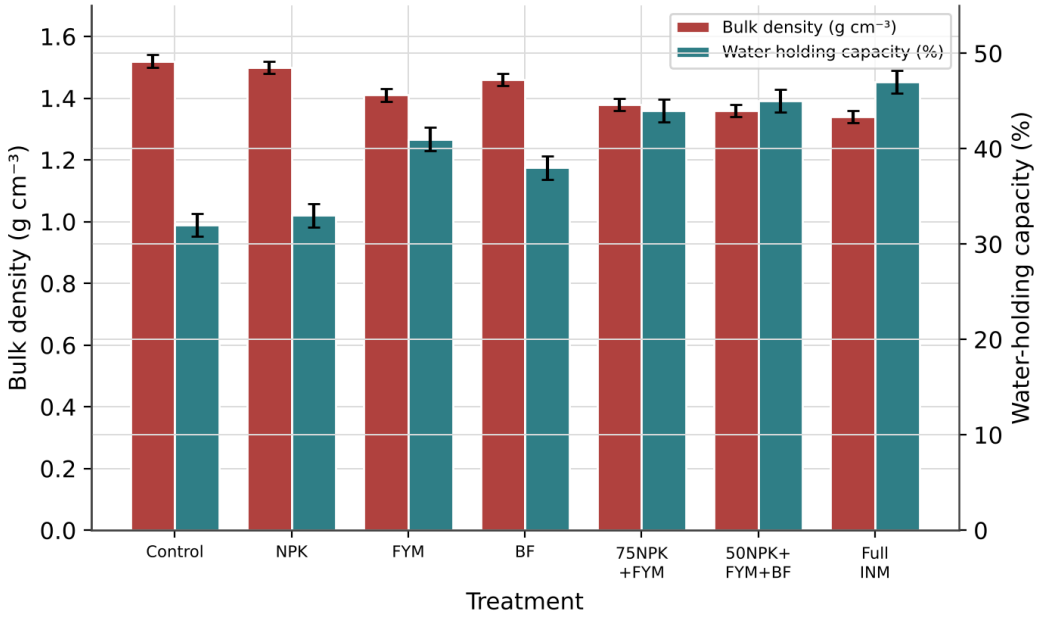

Figure 5. Soil bulk density and water-holding capacity by treatment (means with standard-error bars). The organic-containing treatments lowered bulk density and raised water-holding capacity.

The nutrient uptake by the crop, shown in Figure 7 and reported in Table 1, was highest under the integrated treatments, reflecting both the greater supply of nutrients and the improved soil conditions for their uptake, and it paralleled the yield. The relationship between the soil microbial biomass carbon and the grain yield, shown in Figure 6, was strongly and significantly positive, with a correlation coefficient of 0.89, linking the biological health of the soil to its productivity and indicating that the treatments that built the microbial biomass also produced the highest yields. This relationship connects the soil-health benefit of integration to its agronomic benefit, supporting the interpretation that the improvement in the biological fertility of the soil contributed to the improvement in productivity.

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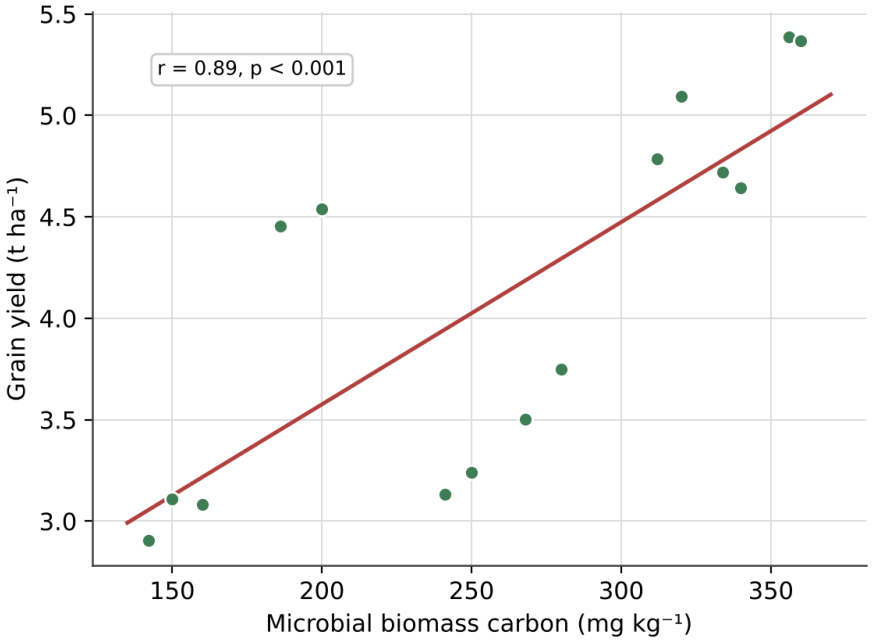

Figure 6. Relationship between soil microbial biomass carbon and grain yield across plots. The strong positive correlation links the biological health of the soil to its productivity.

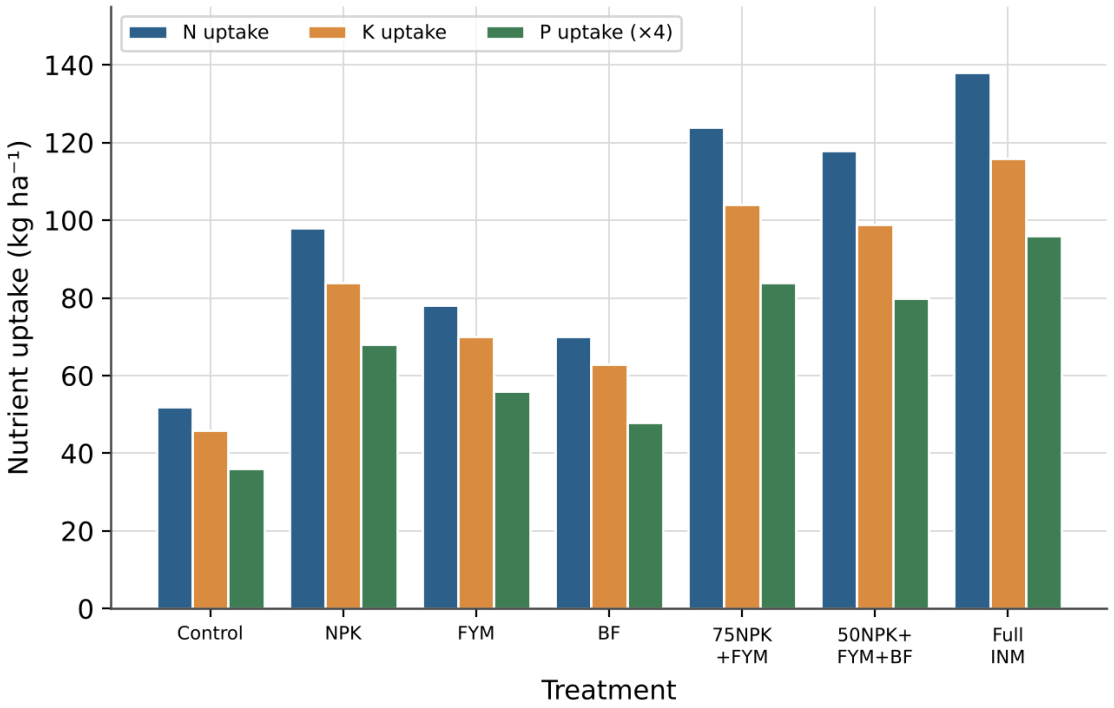

Figure 7. Nutrient (N, P, K) uptake by the crop by treatment (means). Uptake was highest under the integrated treatments; P uptake is shown multiplied by four for display.

Taken together, the results demonstrate that full integrated nutrient management produced the highest grain yield, above that of inorganic fertilizer alone, together with the highest soil microbial biomass, soil organic carbon, available nutrients, and water-holding capacity and the

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lowest bulk density, and that the soil-health benefits were conferred by the organic and biological components that inorganic fertilizer alone did not provide, with the microbial biomass strongly correlated with the yield.

5. Discussion

The two-season field study reveals that the use of integrated nutrient management (INM) system (inorganic nutrient addition to soil along with organic manure and biofertilizer) increase the productivity of the crop over inorganic nutrient addition and significantly improve the microbial, chemical and physical properties of the soil. The yield of full integrated nutrient management was the highest at 5.3 t ha^{-1} compared with 4.4 t ha^{-1} for inorganic fertilizers alone and the highest soil microbial biomass carbon, soil organic carbon, available nutrients, water-holding capacity and the lowest bulk density were obtained in this treatment, and the soil microbial biomass was highly correlated with the yield. These results demonstrate that integrated nutrient management could be used to obtain high productivity while also providing better soil health, which combines the best attributes of inorganic nutrient sources, organic nutrient sources, and biological nutrient sources.

The results are consistent with and build on the existing literature on integrated nutrient management. The yield advantage of integration compared to inorganic fertilizer alone and the betterment of the soil properties confirms results of the field studies and long-term experiments that integration does not compromise yield but improves soil quality [7, 9, 12]. The different way that the microbial biomass, the soil organic carbon and the physical properties react to the organic inputs compared with the inorganic inputs confirms the known difference between the soil building and the soil depleting effect of these two types of input respectively, as well as the known correlation of the biological health of the soil with its productivity [4,8,14]. The study, therefore, validates, in a two-season field experiment, the main rationale for integrated nutrient management, namely the dual productivity and soil-health benefit.

This is the main conclusion of the study and is important to highlight: the soil-health indicators' responses differ from the yield's responses to the various sources. The use of inorganic fertilizer alone significantly improved the yield above the control, and showed small increases in microbial biomass, soil organic carbon and physical properties, indicating that the nutrient supply was immediately productive but did not allow for the development of the biological and physical fertility of the soil. The organic containing treatments, on the other hand, significantly increased the soil health indicators and the combination of the organic and biological inputs with the inorganic fertilizer resulted in an increase in the yield of the fertilizer and the soil building of the organic inputs. This difference is why comparing on yield alone would underestimate the value of integration over inorganic fertilizer alone: the key benefit of integration over inorganic fertilizer alone is the long-term maintenance and improvement of soil health to support productivity, which inorganic fertilizer does not support. Thus, the soil health and the productivity of this study is essential for the proper evaluation of integrated nutrient management.

The soil microbial biomass is of special interest as an indicator and its relationship with yield should be highlighted. The microbial biomass reacted significantly and rapidly to the organic inputs compared to the soil organic carbon, which changed much more slowly, indicating that it is a sensitive and early indicator of soil health changes in response to management, and can provide insight into the biological improvement in the soil as the result of the integration, before the complete change in soil organic carbon has occurred. It has also been shown to have a very positive correlation with the yield and therefore the biological health of the soil is connected to the agronomic output of the soil, as the microbial biomass drives the cycling of nutrients and building of organic matter to support crop growth. This not only confirms the use of the microbial biomass as an indicator of both the agronomic and the biological benefit of integration but also helps to explain how this increase in biological health leads to productivity increase due to improved

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biological supply of nutrients provided by the larger, more active microbial biomass.

There are some caveats to the interpretation of these findings. The study was carried out on a single site across two seasons, and while this approach demonstrated more than one season, the advantages of integrated nutrient management (and the differences between the soil health from integrated nutrient management and from applying inorganic fertilizer alone) is seen over many years as the long-term experiments indicate, thus a longer study would be needed to see the full benefit. Specific rates and sources (specific farmyard manure and biofertilizer) were applied, and the effects will vary according to the type and level of the organic and biological inputs. The study focused on agronomic and soil effects; the economic evaluation of the cost and availability of the organic and biological inputs and the value of the soil benefit (which is essential to the practical recommendation of the integration) was not considered. Finally, the study quantified a cereal crop in a given system; the benefit on crops and systems would need to be wider.

The practical and economic considerations of integrated nutrient management, while not part of the formal scope of this study, are significant in terms of their importance in the adoption of this system and should be mentioned. The benefit of integration needs to be balanced against the cost of the organic and biological inputs – farmyard manure, where available on the farm or locally, is a low cost input and can also dispose of a waste product, but bulk and labour costs in manure application as well as limited availability of manure in areas with low livestock densities are costs, and biofertilizers are a low cost input but require appropriate storage and application. Of particular economic and environmental interest is the use of alternative organic and biological fertilizer to the inorganic fertilizer in the 75% and 50% treatments which resulted in high yields with a lower amount of inorganic input, thus reducing the environmental impact and the cost of the inorganic fertilizer without compromising yield and soil health. The value of the soil-health benefit (acquired in the long-term) and the availability and cost of the inputs that are required will therefore be crucial for the appropriate degree and form of integration in a given setting, on which such decisions should be based; the agronomic and soil-health responses quantified here are the basis. The long-term perspective is important, because the greatest value of integration is the long-term maintenance of soil health and productivity over years and decades — which a short-term accounting system overlooks.

The implications for practice are obvious. The use of integrated nutrient management (INM) system involves using inorganic fertilizer in combination with organic manure and biofertilizer which is found to boost crop productivity compared to organic fertilizer alone and also promote microbial, chemical and physical health of soil, which will make it more sustainable as compared to inorganic fertilizer usage that reduces soil health over time. The priorities for practice include adoption of integration in a form and level appropriate to the availability and cost of the inorganic and organic/biological inputs; partial replacement of inorganic fertilizer by organic and biological inputs and recognizing the benefit to soil health rather than yield; and the trade offs for partial replacement of inorganic fertilizer, whether by organic and biological inputs or by the absence of inorganic fertilizer, in terms of yield and cost, and environmental impact. The long-term assessment of benefit, evaluation across crops, systems and input sources, and economic analysis of integration are the priorities for research. The overall lesson is that sustaining soil fertility involves bringing together the inorganic, organic and biological inputs of soil fertility, linking the short-term productivity of inorganic with the soil building of organic and biological nutrients; and that only the combination of the inorganic, organic and biological source of soil fertility can

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deliver high productivity and soil health that none of those three sources can deliver on its own.

6. Conclusion

Soil fertility is a condition that needs to be maintained to ensure the sustained productivity of intensive cropping and integrated nutrient management aims to bring together high productivity and building soil health through the use of organic manure and biofertilizer along with inorganic fertilizer. Based on this two-season field study, the findings indicate that the highest grain yield (5.3 t ha-1) was obtained with full integrated nutrient management while inorganic fertilizer alone and soil unfertilized (control) yielded 4.4 and 2.9 t ha-1, respectively, and that the soil microbial biomass was significantly and positively correlated with grain yield. The benefits to the soil health – increased microbial biomass, organic carbon, and water holding capacity and reduced bulk density – was not what the inorganic fertilizer could have offered alone, but the combination of the two was the greatest benefit – integrating immediate fertility of the fertilizer with the soil building properties of relying on the fertilizer alone. Central findings are that the use of integrated nutrient management can boost crop productivity beyond that of the inorganic fertilizer alone, and that the microbial, chemical and physical health of the soil can also be improved, with the potential to provide a sustainable alternative to inorganic fertilizer whose full, long-term benefit can be optimized, along with the economic benefit of the input and system, which requires further study.

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