Earthworm community, Soil fertility and Soybean Performance under Integrated Nutrient Management in Black Clay Soils of Sagar District, Madhya Pradesh, India.

Sanjay Dohare and Sunita Singh

Government Girls P. G. College of Excellence, Sagar M.P.

Email: dohareanjay@gmail.com

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Abstract

Earthworms are playing a pivotal role in agricultural soils as their feed, burrow and cast in a way that affects soil structure, nutrient availability, microbial processes and water relations. They are also land management sensitive and can be useful biological indicators of soil condition. In the present study, the earthworm ecology in soybean cultivated black soil of the Sagar district, Madhya Pradesh in India was evaluated with emphasis on impact on earthworms caused by conventional chemical cultivation practices and integrated nutrient management (INM) wherein vermi-composting along with chemical fertilizer was used. The experiment was laid out in a controlled pot at three sites namely, Khurai, Patqui and Rehli having with 5 pots of each treatment. The physico-chemical properties of soil and earthworm-cast, soybean growth and yield, and earthworm species composition, ecological categories, density and biomass, were evaluated. A total of eight species of earthworms (representative of three ecological groups) were observed. In the experimental INM treatment, all 8 species were supported while the conventional treatment supported 7 species. The mean earthworm density, raised from 45.0 individuals m−2 with conventional management to 82.7 individuals m−2 with INM, and biomass from 21.1 to 42.5 g m−2 with INM management. Simpson diversity, evenness and Shannon diversity was increased from 0.76 to 0.84, 0.82 to 0.93 and 1.60 to 1.93 respectively. INM also increased soil moisture, reduced bulk density and available N, P, K, S and micronutrients significantly and organic carbon from 0.52 to 0.78%. The enrichment ratio ranged from 1.72 (for organic carbon) to 1.41 (available nitrogen), 1.78 (available phosphorus) and 1.45 (available potassium) in the earthworm casts when compared to the surrounding soil. Soybean grain yield was improved from 14.2 to 21.8 q ha-1, with significant improvement in pods per plant, seed yield per plant and biological yield. Organic C, as well as soil nutrient and grain production had highly positive correlation with earthworm biomass and density. Results indicate that INM improves simultaneously biological, edaphic and agronomic aspects of the soybean agro-ecosystem and it can be used as practical bio-indicators of soil health for central Indian black clay soils.

Keywords: Earthworms, ecosystem engineers, bio-indicators, integrated nutrient management,vermicompost, soybean, soil fertility, black clay soil, Sagar district, Madhya Pradesh.

1. Introduction

Soil is not only a chemical property but also a result of interactions between mineral particles, organic matter, water, root, microorganisms, soil fauna. Earthworms are one of the most important faunal groups due to their physical modification of productive agricultural soils and their chemical impact on nutrient cycling and soil biology. They influence their environment in a number of ways including consuming soil and plant debris, producing nutrient-rich casts, creating burrows and stable aggregates, redistributing organic matter and creating microsites favorable to microbial activity. These factors make earthworms ubiquitous "ecosystem engineers" as they are components of the soil that alter the environment in ways that affect other organisms and ecosystem processes (Blouin et al., 2013; Al-Maliki et al., 2021; Medina-Sauza et al., 2019).

Earthworms have an engineering influence at multiple scales. On gut scale mixing and alteration of soil and organic residues are occurring, leading to formation of casts of different chemical and biological properties. Burrows, at the profile scale, impact porosity, aeration, infiltration, drainage and root penetration. The community living cycle of earthworms may influence the stability of the aggregate, the stratification of organic material, and the effective fertility of the rooting zone when it interacts with the earthworm community for several successive seasons at the field scale. As burrows and casts can persist, the ecological effects may last beyond the life of the worms which have produced them. The combination of these ones renders the earthworms particularly relevant to agroecological systems where soil structure and water holding capacity are limiting factors.

Earthworms are good bio-indicators of soil health. Their abundance, biomass, species richness, and ecological composition, integrate the effects of soil moisture and organic carbon, soil pH and soil nutrient levels, physical disturbance and chemical inputs over time. The earthworm community is a reflection of the impact of management and the environment rather than one chemical measure, which reflects the status of the soil at the time that soil was sampled. In general, soils under intensive management strategies, with zero or minimum organic inputs and frequent chemical or mechanical disturbance, support lower numbers and less functional unpredictable earthworm communities, while soils that receive organic matter and experience less chemical or mechanical disturbance, support higher earthworm densities, biomass, and additional diversity (Postma-Blaauw et al., 2010; Sankar and Patnaik, 2018; Singh et al., 2020a).

Earthworms are distinguished into three ecological groups: epigeic, endogeic and anecic which strengthens the functional interpretation. Epigeic forms stay in the soil surface, feed on fresh organic tissues and can play a major role in litter fragmentation. Endogeic forms can help to form extensive horizontal burrow networks when inhabiting and feeding within mineral soil, mixing organic and mineral soil. Anecic types create more or less permanent holes in the vertical direction and move surface residues to the base of the soil.

Earthworm ecology is more relevant in the soybean production system in Madhya Pradesh, India. Soybean, *Glycine max* (L.) Kharif oilseed and protein crop of central India, Merr., is highly indicative to the black clay soil of the region. This production belt includes Sagar district, and here agriculture is totally dependent upon monsoon rainfall, soil moisture levels fluctuate considerably from season to season, and soils are fine textured, black, swells when wet and cracks when dry. During the rainy season these soils can have a lot of water in them, but the high clay content and affinity of the same for seasonal shrink-swell can make it problematic for aeration, workability and root growth. Management practices that raise organic matter and biological activity and enhance structural stability therefore have special significance.

Mineral fertilizers and pesticides are often heavily used in conventional soybean production in the region. These inputs can yield high crop production in the short term, but repeated stimulation of soils with high levels of chemical fertilizer in the absence of necessary additions of organic matter can lead to lower soil organic carbon levels, lower soil aggregation and less soil biology. Also, soil-faunal communities can shift due to agricultural intensification, resulting in changes in nutrient turnover and in soil resilience at the long term (de Graaff et al., 2019; Pelosi et al., 2014). In contrast to this, integrated nutrient management provides an alternative whereby mineral fertilizers are used along with organic sources like farmyard manure or compost/vermicompost. Vermicompost provides nutrients, biologically active organic matter and has been associated with improved soil physical condition and nutrient supply, as well as crop performance (Joshi et al., 2015, Yadav et al., 2018).

Soybean agronomy and fertilizer management have been studied in detail but the biological aspects of soil fertility in Soybean fields of Sagar district in India has received less systematic study. Specifically, little integrated information is available on earthworm community structure, cast structure, soil chemistry and soybean growth and yield resulting from different nutrient-management practices in blacks soils in the district. This gap is pertinent, since in the same management practice, a beneficial impact on the soil fauna may impact on the soil environment and on crop performance. Thus, studies on these components alone can overlook the link between management and agro-ecosystem function.

Therefore, the present investigation was planned to bridge up this gap, by comparing the conventional chemical cultivation to the INM using chemical fertilizer and vermicompost. The goals were: (i) to describe earthworm community (species composition, ecological type, density, biomass, relative abundance, dominance and diversity) and bulk soil-enrichment, and to quantify cast-enrichment, under the two nutrient management regimes; (ii) to describe the growth and yield of soybeans under the two nutrient management regimes; and (iii) to relate earthworm community characteristics, bulk soil-enrichment, and cast-enrichment to soybean growth and yield. The main hypothesis was that with addition of the organic component of INM more favorable soil habitat would be created, which would result in a greater and more complete assemblage of earthworms and a better availability of soil nutrients, and this would in turn result in higher productivity of soybean.

2. Materials and Methods

2.1 Study area and experimental framework

This study was conducted in Bundelkhand, central India in Sagar district of Madhya Pradesh, India. To sample the black clay agriculture soils of the district three points Khurai, Patqui and Rehli were selected, all of which are soybean growing locations. Its regional climate is subtropical with a hot and dry summer, and a cool dry winter and a warm and humid monsoon. Earthworms are most active during the soybean growing season from July through September, when most of the rainfall occurs. The black clays are fine textured, moisture retentive in the wet-season and hard and cracked in dry season. The soil organic matter and biological structure is of particular importance for crop and soil-fauna functioning as their physical behaviour is seasonal.

Controlled pot experiment was the principal experimental comparison used. Two nutrient-management treatments were arrived with one being conventional treatment with chemical fertilizer which is practiced here and INM to be its experimental treatment of vermicompost along with chemical fertilizer. The treatments were replicated five times, pot being considered as the experimental unit. All treatments received the same soybean variety, sowing procedures, cultural management, environmental exposure, and moisture regime with the only major difference being nutrient management. Each experiment was repeated with the soil typical of the three sites in order to compare the effects of the treatments against the soil differences.

2.2 Soil and pot preparation

The black clay soil used was obtained from the soybean field, the stones and coarse roots and debris were removed from it, and the large clods were broken up so that the soil was relatively uniform. Equivalent amounts of soil were placed in each pot. Finally, an organic substrate (cow dung) was added evenly, and should not therefore be regarded as a treatment difference in terms of soil biology. The soil was stabilized for about 45 days with the prepared soils before sowing of soybean and introducing earthworms. The moisture content in each of the pots was kept at an intermediate and similar level in all pots so that neither water logging nor dryness did occur. Drainage was provided and pots were kept in natural light and temperature condition within the crop season.

2.3 Earthworm sampling and community analysis

Earthworms were taken from each sampling point and processed according to standardized soil-zoological methods that were common to every site, treatment and sampling date. Specimens were collected, counted and weighed, preserved appropriately and identified using morphological and taxonomic characters. Using recognized ecological species description, epigeic, endogeic and anecic species were attributed to each species. Community structure was measured in terms of density, biomass, relative abundance and species dominance. The Shannon diversity index (H′), Simpson diversity and Simpson reciprocal index, Margalef richness and Pielou evenness and Berger-Parker dominance were used to assess diversity. Seasonal patterns were assessed for the monsoon and post-monsoon and summer seasons, while monthly observations were used to give a description of the temporal change for the active crop season.

2.4 Soil and earthworm-cast analysis

Soils were retrieved in bulk and earthworm manure in casts and analysed using standard soil-chemical procedures. pH, electrical conductivity, moisture content, bulk density, organic carbon, available nitrogen, phosphorus, potassium, sulphur, exchangeable calcium and magnesium and DTPA extractable zinc, iron, manganese and copper were measured. Organic C was calculated as per Walkley-Black procedure, available N, P and micronutrients were the standard procedures as cited in the methodology of the thesis (Olsen et al., 1954; Lindsay and Norvell, 1978; Subbiah and Asija, 1956; Jackson, 1973). The concentration in earthworms was compared to bulk soil and enrichment ratios computed, as concentration in casts/ concentration in bulk soil. The processing trend by earthworms for enrichment with values > 1 reached significance.

2.5 Soybean growth and yield measurements

Soybean growth stages were used to assess soybean growth. Plant height, the number of branches per plant, number of leaves per plant, root nodules and dry matters were measured at three different dates 30, 60 and 90 days after sowing (DAS). Pods per plant, seeds per pod, 100-seed weight, seed yield per plant, biological yield per plant, harvest index and grain yield and stover yield were measured at harvest stage. The measurement procedures were the same for all experimental units and to ensure direct comparisons between treatment means.

2.6 Statistical analysis

Summarization of data was carried out as treatment means, site means and with measures of the variation, when replicated data were available at the replicate level. To assess the significance of any differences between treatments, analysis of variance (ANOVA) was employed and $p < 0.05$ was considered as statistically significant. The effect of the treatments was quantified by using F values and probability levels for several important soil and crop parameters. Pearson type correlation analysis was used to determine the correlation among earthworm density, biomass, diversity and soil organic carbon, available nutrients, soil moisture and grain yield. These correspondences were taken to indicate a coordination of these biological, edaphic and agronomic elements, and not a one-way causation.

3. Results

3.1 Species composition and functional structure

During the study, 8 species of earthworm were found: Metaphire posthuma, Lampito mauritii, Octochaetonabeatrix, Perionyx excavatus, Drawida willsi, Amynthasdiffringens, Eutyphoeus waltoni and Polypheretima elongata. There were three ecological categories shown in the fauna. M. posthuma, O. beatrix, D. willsi and P.elongata were characterized as endogeic species, P. excavatus and A. diffringens as epigeic and L. mauritii and E. waltoni as anecic species. All eight species were found in the INM treatment and seven were found in the conventional treatment. E. waltoni was found only under INM which showed that integrated treatment favored a more complete functionally assemblage.

The density of total earthworm was 45.0 individuals/m2 in conventional and 83.0 individuals/m2 in INM. Comparatively, under conventional management, the number of M. posthuma individuals was found to be the highest with an average of 35.56%, followed by P. excavatus (26.67%) and A. diffringens (15.56%). The share of L. mauritii was very small at 3.33% and P. elongata just 1.11%. Dominance was more spread under INM. The proportional dominance of M. posthuma dropped to 26.51%, with an increasing proportional dominance of L. mauritii (16.87%), O. beatrix (14.46%), D. willsi (10.84%) and E. waltoni (4.82%) of the community.

Table 1.1. Earthworm species recorded in the soybean fields of the study area, with their families and ecological categories, and their occurrence under the two treatments.

Species	Family	Ecological category	Occurrence
Metaphire posthuma	Megascolecidae	Endogeic	C+E
Lampito mauritii	Megascolecidae	Anecic	C+E
Octochaetona beatrix	Octochaetidae	Endogeic	C+E
Perionyx excavatus	Megascolecidae	Epigeic	C+E
Drawida willsi	Moniligastridae	Endogeic	C+E
Amynthas diffringens	Megascolecidae	Epigeic	C+E
Eutyphoeus waltoni	Octochaetidae	Anecic	E

Polypheretima elongata	Megascolecidae	Endogeic	C+E

An significant treatment separation was found in the ecological-category structure. Epigeic (42.22%), endogeic (54.44%) and anecic (3.33%) epigeo-forms do not occur in comparable numbers in the conventional treatment. Epi-, endogeic and anecic forms accounted for 22.89%, 55.42%, 21.69% INM. Therefore, the overall endogeic representation was not affected, but in the case of INM, there was a remarkable increase in the proportion of deep burrowing anecic elements. This change reflects an increased functional breadth, due to the role played by anecic worms in the formation of long-lived vertical macropores and the translocations of organic residues in deeper soil horizons.

3.2 Density, biomass, spatial and seasonal variation

In all 3 localities, the biomass and density of INM was higher when compared with conventional. At Khurai, density increased from 48.0 ± 3.1 to 86.0 ± 4.4 individuals m−2 and biomass from 22.4 ± 1.6 to 44.6 ± 2.8 g m−2. At Patqui, density increased from 42.0 ± 2.7 to 79.0 ± 3.9 individuals m−2 and biomass from 19.8 ± 1.4 to 40.2 ± 2.5 g m−2. At Rehli, density increased from 45.0 ± 2.9 to 83.0 ± 4.1 individuals m−2 and biomass from 21.1 ± 1.5 to 42.8 ± 2.6 g m−2. Pooled means of density and biomass were 45.0 and 21.1 individuals m−2 and 82.7 and 42.5 g m−2, respectively. At all locations, Khurai had consistently high values, and Patqui had consistently low values, however, INM maintained the highest values.

Table 1.2. Species-wise mean density (individuals m^{-2}) and relative abundance (%) of earthworms under the two treatments.

Species	Density (C)	Rel. ab. % (C)	Density (E)	Rel. ab. % (E)
Metaphire posthuma	16.00	35.56	22.00	26.51
Lampito mauritii	1.50	3.33	14.00	16.87
Octochaetona beatrix	5.00	11.11	12.00	14.46
Perionyx excavatus	12.00	26.67	11.00	13.25
Drawida willsi	3.00	6.67	9.00	10.84
Amynthas diffringens	7.00	15.56	8.00	9.64
Eutyphoeus waltoni	0.00	0.00	4.00	4.82
Polypheretima elongata	0.50	1.11	3.00	3.61
Total	45.00	100.00	83.00	100.00

A strong seasonal variation was noted. With conventional management, density averaged 45.0 individuals m−2 during the monsoon, while 82.7 individuals m−2 were recorded under INM and 21.1 and 42.5 g m−2 of biomass were found, respectively. Densities in the post monsoon period were reduced to 33.0 individual m−2, biomasses to 15.4 and 31.2 g m−2. Summer values were lowest: 15.0 versus 29.0 individuals m−2 and 6.8 versus 14.6 g m−2. The same trend was observed in each month with the month of August giving the highest intake and gradually decreasing from October through December. The seasonal response was high, pointing to high influence of soil moisture and temperature, whereas the consistent difference among the treatments suggests nutrient management changed habitat quality within seasonal conditions.

3.3 Diversity and dominance

The diversity of the communities under INM was always more. The number of species jumped from seven to eight species. The Shannon index rose from 1.60 with conventional management to 1.93 with INM and the Simpson diversity (1 − D) rose from 0.76 to 0.84 favouring INM. The Simpson reciprocal diversity rose from 4.17 to 6.18. Evenness increased from 0.82 to 0.93 according to Pielou's evenness and dominance based on Berger-Parker decreased from 0.36 to 0.27. This resulted in both treatments having a margin alef richness value of 1.58, as the number of species added was accompanied by a marked rise in the total abundance. The same trend was observed in site-level indices: Khurai had the highest and Patqui the lowest whereas for Rehli, the diversity and evenness were intermediate but increased for all sites with INM.

Table 1.3. Composition of the earthworm community by ecological category (% of total density) under the two treatments.

Ecological category	Control (%)	Experimental (%)
Epigeic	42.22	22.89
Endogeic	54.44	55.42
Anecic	3.33	21.69
Total	100.00	100.00

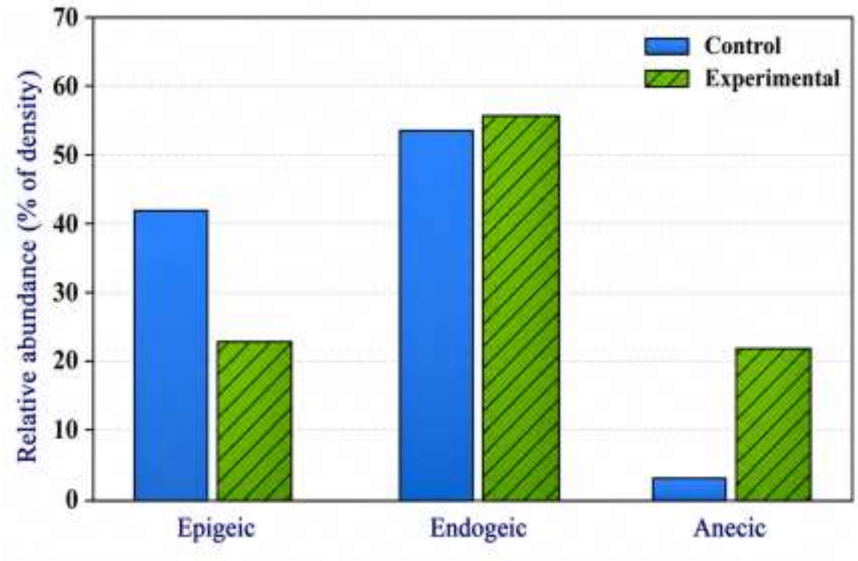

Figure 1.1. Relative abundance of the epigeic, endogeic and anecic ecological categories (% of total density) under the control and experimental treatments.

The increase in worm numbers was accompanied by a higher richness, higher evenness and lower dominance indicating the success of INM to do more than merely provide an increase in the total number of worms. It shifted the community structure (Putnam, 1941) to a more even species organization in which more species played significant roles. Return or maintenance of anecic species particularly important - from functional standpoint.

3.4 Soil physico-chemical properties

It was found that INM caused good physical and chemical properties in the black clay soil. Soil moisture increased from 18.4 ± 0.50% to 22.7 ± 0.60% ($F = 28.6$, $p < 0.01$), while bulk density decreased from 1.38 ± 0.02 to 1.26 ± 0.02 g cm−3 ($F = 18.9$, $p < 0.01$). Organic carbon increased from 0.52 ± 0.02 to 0.78 ± 0.03% ($F = 46.2$, $p < 0.01$). The electrical conductivity increased slightly from 0.28 to 0.34 dS m−1 ($p < 0.05$), although the value was still in the non-saline range and the soil pH decreased slightly from 7.82 ± 0.06 to 7.64 ± 0.05 ($p < 0.05$).

There were significant increases in the availability of major nutrients. Available nitrogen increased from 218.0 ± 5.4 to 286.0 ± 6.8 kg ha−1 ($F = 61.4$, $p < 0.01$), phosphorus from 14.2 ± 0.6 to 21.6 ± 0.8 kg ha−1 ($F = 55.1$, $p < 0.01$), and potassium from 268.0 ± 6.2 to 322.0 ± 7.1 kg ha−1 ($F = 32.7$, $p < 0.01$). Available sulphur increased from 11.4 ± 0.5 to 16.8 ± 0.6 mg kg−1 ($F = 44.0$, $p < 0.01$). The exchangeable calcium and the exchangeable magnesium content also rose significantly as a result of the amendments ($p < 0.05$), from 32.1 to 36.4 cmol kg−1 and from 8.6 to 10.2 cmol kg−1, respectively.

Micronutrients also showed positive responses. DTPA-extractable zinc increased from 0.58 ± 0.03 to 0.92 ± 0.04 mg kg−1, iron from 4.62 ± 0.18 to 6.18 ± 0.22 mg kg−1, manganese from 5.14 ± 0.20 to 6.85 ± 0.24 mg kg−1 and copper from 1.12 ± 0.05 to 1.48 ± 0.06 mg kg−1; all differences were significant at $p < 0.01$. These site-level data demonstrated that the Khurai had slightly higher nutrient values, and Patqui had lower values; the effect of treatment was consistent across sites.

3.5 Earthworm-cast enrichment

Most fertility related soil parameters were higher in the earthworm casts, which were also chemically different from the surrounding INM soil. The level of organic carbon was found to be 0.78% in the surrounding soil, while casts contained 1.34% with an enrichment of 1.72. Available nitrogen increased from 286 to 402 kg ha−1 (ratio 1.41), phosphorus from 21.6 to 38.4 kg ha−1 (ratio 1.78), potassium from 322 to 468 kg ha−1 (ratio 1.45) and sulphur from 16.8 to 24.6 mg kg−1 (ratio 1.46). The enrichment ratio of calcium and magnesium was 1.18 and 1.33, respectively, in both exchangeable form. Micronutrient enrichment was also marked: zinc increased from 0.92 to 1.68 mg kg−1 (ratio 1.83), iron from 6.18 to 9.42 mg kg−1 (ratio 1.52), and manganese from 6.85 to 9.98 mg kg−1 (ratio 1.46). The cast pH was found to be slightly lower than the surrounding soil (7.38 vs. 7.64).

These differences show the effect of earthworm gut on the transformation of nutrients in the process of gut passage and cast formation. The casts served as nutrient rich microsites within the bulk soil, and were the most direct mechanistic connection between earthworm activity and enhanced nutrient availability.

3.6 Soybean growth response

INM was well responded during the crop cycle in soybean. At 30 DAS, plant height increased from 14.2 to 17.6 cm, branches per plant from 2.1 to 2.8, leaves per plant from 8.4 to 10.6, root nodules from 9.2 to 14.6 and dry matter from 1.8 to 2.6 g plant−1. After 60 DAS differences were accentuated: plant height (38.5 and 47.2) and branches (4.6 and 6.2) under conventional management and under INM, respectively; leaves (21.3 and 27.8) under conventional management and under INM, respectively; nodules (22.4 and 32.8) and dry matter (8.4 and 12.1 g plant−1) under conventional management and under INM, respectively. At 90 DAS, plant height reached 52.8 versus 63.4 cm, branches 5.8 versus 7.4, leaves 24.6 versus 31.2, root nodules 18.6 versus 27.4 and dry matter 14.2 versus 20.3 g plant−1. The greater difference at the later stages is consistent as it means that the benefits of better soil condition, as a result of the improved soil condition, carried over through the crop cycle.

3.7 Yield and yield components

The greater vegetative response resulted in significant yield benefits. Pods per plant increased from 38.4 ± 1.5 to 54.6 ± 1.9 ($F = 44.8$, $p < 0.01$), seeds per pod from 2.30 ± 0.05 to 2.60 ± 0.06 ($p < 0.05$), and 100-seed weight from 10.8 ± 0.3 to 12.4 ± 0.3 g ($p < 0.01$). Seed yield per plant increased from 9.60 ± 0.40 to 15.80 ± 0.60 g ($F = 66.3$, $p < 0.01$), while biological yield increased from 22.4 ± 0.8 to 33.6 ± 1.1 g plant−1 ($F = 58.2$, $p < 0.01$). Harvest index increased from 42.9 to 47.0% ($p < 0.05$).

Table 1.4. Mean density (individuals m^{-2}) and biomass (g m^{-2}) of the earthworm community at the three sites under the two treatments (mean ± SE).

Site	Density (C)	Density (E)	Biomass (C)	Biomass (E)
Khurai	48.0 ± 3.1	86.0 ± 4.4	22.4 ± 1.6	44.6 ± 2.8
Patqui	42.0 ± 2.7	79.0 ± 3.9	19.8 ± 1.4	40.2 ± 2.5
Rehli	45.0 ± 2.9	83.0 ± 4.1	21.1 ± 1.5	42.8 ± 2.6
Pooled mean	45.0	82.7	21.1	42.5
F value / significance				

Grain yield was 14.2 ± 0.5 q ha−1 under conventional cultivation and 21.8 ± 0.7 q ha−1 under INM ($F = 72.1$, $p < 0.01$), an increase of approximately 53.5%. Stover yield increased from 18.6 ± 0.6 to 26.4 ± 0.8 q ha−1 ($p < 0.01$). At Khurai, grain yield was 15.1 versus 23.0 q ha−1; at Patqui, 13.3 versus 20.6 q ha−1; and at Rehli, 14.2 versus 21.8 q ha−1. Site differences were found as were the earthworm and soil variables, but did not affect the direction of the treatment effect.

3.8 Earthworm-soil-crop relationships

Analysis of the correlative relationships identified a coordinated pattern of positive relationships. Biomass (r = 0.94) and Shannon diversity (r = 0.88) were highly correlated with the density of earthworms, as were soil organic carbon (r = 0.89), available nitrogen (r = 0.85), available phosphorus (r = 0.81), soil moisture (r = 0.79), and grain yield (r = 0.86). The earthworm biomass correlated with soil moisture (R = 0.77), organic carbon (R = 0.91), available phosphorus (R = 0.80), available nitrogen (R = 0.83) and grain yield (R = 0.88). Shannon diversity positively correlated with organic carbon (r = 0.82) and grain yield (r = 0.82). Organic carbon (r = 0.88), available N (r = 0.85), available P (r = 0.80) and soil moisture (r = 0.75) were highly correlated with grain yield.

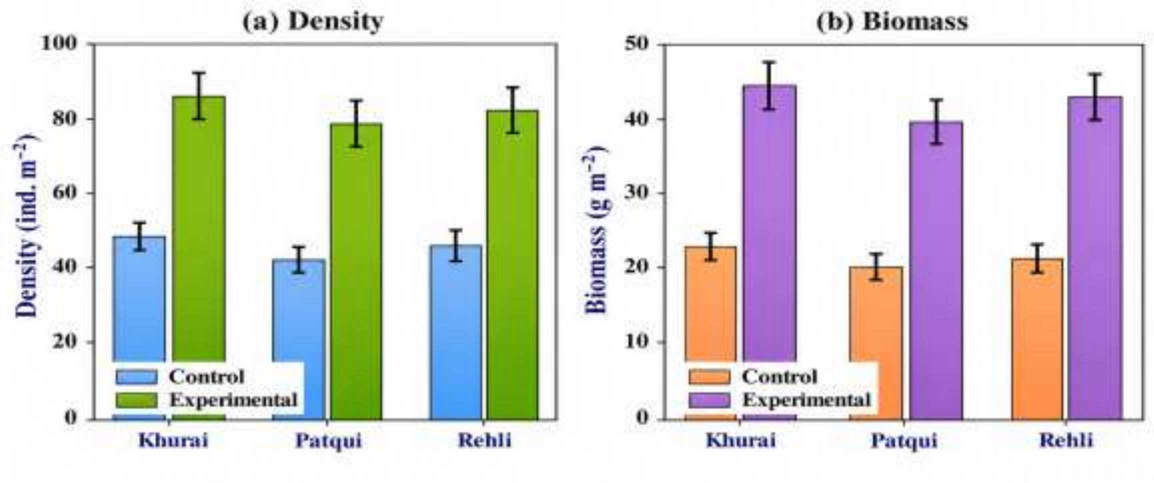

Figure 1.2 Mean density (a) and biomass (b) of the earthworm community at the three sites under the control and experimental treatments; error bars denote standard errors.

Table 1.5. Site-wise mean density (individuals m^{-2}) of the recorded earthworm species under the two treatments.

Species	Khu (C)	Reh (C)	Pat (C)	Khu (E)	Reh (E)	Pat (E)
Metaphire posthuma	17.1	16.0	14.9	23.5	22.0	20.5
Lampito mauritii	1.6	1.5	1.4	14.9	14.0	13.1
Octochaetonabeatrix	5.3	5.0	4.7	12.8	12.0	11.2
Perionyx excavatus	12.8	12.0	11.2	11.7	11.0	10.3
Drawida willsi	3.2	3.0	2.8	9.6	9.0	8.4
Amynthasdiffringens	7.5	7.0	6.5	8.5	8.0	7.5
Eutyphoeus waltoni	0.0	0.0	0.0	4.3	4.0	3.7
Polypheretima elongata	0.5	0.5	0.5	3.2	3.0	2.8

The results of the correlation revealed that the biological, chemical and agronomic responses were not independent of each other. Additionally, more numerous and varied earthworm communities were correlated with a greater organic carbon content, nutrient availability and soybean yield through pots and sites. Although a unidirectional causal pathway cannot be established through correlations alone, the pattern is indicative of the proposed mechanism, whereby the profile of organic amendment resulted in an improved habitat, an increase in earthworm-induced soil transformation, and an improved soil environment for crop growth.

4. Discussion

The study reveals consistent and integrated reactions to nutrient use by the soybean agro-ecosystem. INM has been superior in terms of species composition, functional groups, density, biomass, diversity, soil physical condition, nutrient status, cast chemistry and crop yield as compared to conventional chemical cultivation, across species composition, functional groups, density, biomass, diversity, soil physical condition, nutrient status, cast chemistry and crop yield. What is important about this result is that it is coherent. The number of degrees of change was not the answer—the overall trend of the biological, edaphic and agronomic indicators was the same.

INM increased the earthworm biomass nearly twofold and the density of earthworms greatly, which correspond to the ecological needs of earthworms. Organic amendments enhance microbial activity, reduce mineral soil's physical harshness, hold water and enhance supply of food. Vermicompost is already processed, stabilized nitrogen, phosphate, potash, carbon and microbial populations and are generally more soil friendly. The greater soil moisture and decreased bulk density of the soils under INM would also increase the habitat quality by reducing desiccation stress and mechanical resistance. The mechanisms align with studies that have found improved abundance and community complexity of earthworms with less intensive or more biology-based management (Postma-Blaauw et al., 2010; de Graaff et al., 2019; Betancur- Corredor et al., 2024).

Changes in functional category are particularly important. Anecic worms were only few in conventional soil and values in INM were over 1/5 of the community. A nec tactic increase in abundance suggests an improvement in the functions of the ecosystem that cannot be determined in any other way than by the increase in anecic earthworms that provide persistent vertical macropores and transport organic material from the surface downwards. The most surface active species dominated at the community level might process litter and deliver lesser deep mixing and lesser persistent macroporosity. Thus the INM treatment enhanced the size and functional completeness of the assemblage of earthworms.

This interpretation is supported by a higher diversity and evenness with INM. Berger-Parker domination downstream decreased reflects that there was less dominance of the community in the most common species. Surface waters will often have sensitive species declining or absent, and tolerant present and numerically dominant. When *Eutyphoeus waltoni* was only present under INM and the higher abundance of *Lampito mauritii* indicate that width that the treatment was integrated and therefore could support a broader ecological range. This is an additional advantage of using earth-worm diversity and functional composition as bio-indicators of the soil management quality (Singh et al., 2020a; Sankar and Patnaik, 2018).

Seasonal variability was to be anticipated in a monsoon-controlled environment. The highest earthworm density and biomass were observed in the wet season and summer had a significant negative effect on them. Activity closely related to soil moisture, as earthworms breathe through wet skin and moisture is essential to their survival. What is important to note is that the difference between the treatments was maintained across seasons. Although INM did not switch off the climatic control on earthworm activity, it increased the biological capacity of the soil under favourable as well as less favourable seasons. This buffering effect is due to a plausible increase in soil moisture observed under INM.

A second line of evidence of the ecological benefits of INM are changes in soil properties. This increase in organic carbon was significant along with a decrease in bulk density and increase in moisture content. These variables are highly correlated. Organic matter aggregates and decreases packing density, increases water holding capacity and supplies microfauna/microflora food. Burrowing by earthworms then reinforces the physical effects, creating pores, mixing of organic materials through the surface soil. Consequently, the observed changes may be a result of the interaction of the added organic amendment with the biological activity that it induced.

Nutrient enhancements were general, not limited to any particular nutrient. All applied nutrients (N, P, K and S), exchangeable Ca and Mg, and the four micronutrients measured, were significantly increased. Vermicompost makes direct contribution in addition to biological transformation as reflected from the earthworms results. Earthworms promote decomposition and microbial turnover as well as changing the chemical form and availability of nutrients through their gut processes. The data on cast clearly point to the enrichment of this process in the current research.

The Cast enrichment ratios are especially telling and are important to look at because they show you how the field is improving on a small level. Casts had significantly higher concentrations of organic C, available N, P, K, S and micronutrients in comparison with the surrounding soil. Amongst measured enrichment ratios, the ratio for phosphorus and for zinc was one of the highest. During passage in the earthworm gut mineralization may be enhanced and nutrient solubility may change due to earthworm digestion, addition of mucus and activation of microorganisms. After deposition, the casts create an area that is rich in nutrients that affect roots, microorganisms and over time the bulk soil fertility. This was similar to the observed effect of cast by earthworms, in previous reports, to engineer soil chemistry (Bhadauria and Saxena, 2010; Singh et al., 2016).

The agronomic impacts were enormous. Grain yield was improved by about 53.5% for INM as well as pod number, seed weight, seed yield per plant and biological yield. Yield data has demonstrated that the yield gain became more pronounced than just at harvest. Plants subjected to INM grew taller, more branched, had more leaves and accumulated more dry matter at each sampling time. The root nodulation was also higher, and the biological nitrogen fixation is a function of successful root nodulation in the soybean. Better soil aeration, nutrient supply, moisture holding capacity and rhizosphere biological activity all would be expected to play a role in this response.

Yield results were in agreement with research conducted with other legumes such as soybean, which demonstrated the advantageous impact of combined systems of nutrient management and Vermicompost (Yadav et al., 2018), Gavit et al., 2024; Khanal et al., 2024). They also agree with the larger body of evidence from meta-analysis that the presence of earthworms can enhance plant production, for instance, through altering nutrient cycling and soil structure (van Groenigen et al., 2014). The present study further tries to add a local context in the central India and exhibits such relationships based on the black clay soils which characterize the soybean growing landscape of Sagar district.

The correlation matrix combines the individual results. The earthworm density and biomass were highly correlated with organic carbon and grain yield and both earthworm variables were positively correlated with soil available N, P and moisture. Organic carbon was in turn strongly related to grain yield. These associations present a conceptual pathway of increases in carbon, the physical environment due to the application of the organic amendment, the diversity of earthworms and their abundance, burrowing and casting, and the transformation of organic matter, with all of these effects combining to favor the performance of the crop. The correlations should not be viewed as evidence for earthworms alone influencing increased yield since the actual experiment involved nutrient-management packages rather than manipulating earthworms alone. However, their power and persistence enabled them to be powerful soil response mediators and indicators.

The results have significance on the soil health side since they prove that monitoring earthworm populations could be a very complementary soil test technique to current chemical soil analysis. Earthworm density, biomass and functional composition is a better indicator of the quality of an environment over time than soil analyses. A field that has a lot of abundant individuals, but is extremely low in functional diversity, may indicate something other than a field containing an even mix of epigeic, endogeic and anecic forms. Simple earthworm assessment may thus be a useful and biologically relevant indicator of whether management is bringing about restoration or deterioration of soil function, for extension and long-term monitoring.

There is also a sustainability aspect to the study. Although black clay soils have a high productivity potential, they are difficult in terms of physical condition, and their future depends on conserving soil structure and organic matter. Using mineral fertilizer alone will bring in nutrients and may not improve carbon inputs or soil biology. INM by contrast is a combination of mineral fertiliser with organic amendments, and the nutrient availability in the amendments is enjoyed shortly after application, whilst the effect of the carbon and biological stimulation and conditioning, is also utilized immediately after application. Based on the present results, it appears that this method can benefit both immediate soybean production and future biological and physical condition for production.

Some weaknesses need to be taken into account. First, the primary experimental comparison was implemented in pots, controlling for the soil properties as well as moisture and inputs, while smoothing out the spatial variation and climatic conditions of open field settings. Effect measured under controlled conditions may vary in extent on application in the field. Secondly, the study was limited to three locations in one district, and black soil; care must therefore be taken in extrapolating to other soil or climate types. Thirdly, seasonal and interannual changes in soil moisture and soil temperature relate to changes in earthworm communities as do also various kinds of management history. A multi-year study is needed, as population stability and recovery following climatic extremes would be better documented in a longer study. Lastly, the correlation between earthworm and soil and crop variables often gives no indication of the specific pathway of action. Efforts to directly monitor the impact of earthworm functional group manipulation while maintaining constant nutrient supply will help determine the absolute contribution of earthworm activity.

The experimental consistency from site to site and from one response variable to another provide confidence in the central conclusion bypassing these limitations. INM developed a biologically more active, chemically more fertile, physically more favourable and agronomically more productive soil environment compared to the conventional soil environment. The earthworm community was sufficiently responsive to act not only as a means of soil transformation, but also as an indicator of the quality of the management regime.

5. Conclusions and Recommendations

The study offers an integrated assessment on earthworm ecology, fertility and productivity of soybean grown under different nutrient-management strategies in black clay soils of Sagar district. Eight species of earthworm were observed, which included species that were epigeic, endogeic and anecic. INM resulted in greater total density, nearly doubled biomass, greater diversity and evenness, smaller dominance and considerably larger anecic component. These are indicators of both soil faunal functional complexity and numerical recovery.

Another improvement area done by INM is soil. Organic carbon along with moisture and macronutrients and micronutrients were increased with a decrease in bulk density. The soil engineering mechanism by which earthworms would contribute to nutrient cycling was clearly illustrated in the casts as there was a significant increase in organic carbon and plant-available nutrients compared to other soil components. Soybean growth improved throughout the crop cycle and grain yield increased from 14.2 to 21.8 q ha^{-1}. A high positive correlation between earthworm density and biomass and soil fertility indicators and grain yield also highlighted the biological, edaphic and agronomic responses.

Based on these results, integrated nutrient management, using vermicompost in conjunction with careful chemical fertilizer use should be promoted for soybean production under black clay of Sagar district and under similar conditions. Management recommendations should include frequent addition of organic matter, avoiding unnecessary soil disturbance, judicious use of pesticides and ensuring soil moisture and residue cover wherever feasible. In addition to traditional chemical measurements, density, biomass, and ecological-group composition of earthworms can be included as biological low-cost indicators in soil-health monitoring.

Future studies will require sustainingresults with repeated trials in field in different seasons, different farm types, quantification of optimum level of vermicompost and fertilizer mixtures and study of economic returns at the level of farmers. On-going research should be conducted to determine if earthworm diversity and soil organic carbon continues to improve over years and if it ultimately leads to less reliance on mineral fertilizers. Molecular identification could be used as an aid for taxonomic confirmation, while using functional-group manipulations could assess the processes of epigeic, endogeic and anecic worms in nutrient cycling, soil structure and soybean yield. The work of this kind would aid in turning scientific evidence into effective regional sustainable strategies for soybean production.

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