Agriculture Association of Textile Chemical and Critical Reviews Journal (2023) 62-71

AATCC Review

13 January 2023: Received
13 May 2023: Revised
15 July 2023: Accepted
14 September 2023: Available Online

www.aatcc.peerjournals.net

Research Article

Open Access

Effect of long term application of FYM and Vermicompost on soil carbon pool, enzymes and microbial activities in Pearl millet-chickpea cropping sequence after 6th crop cycle

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ABSTRACT

The field experiment was carried out on a fixed site at the research farm of Bajra Research Scheme, College of Agriculture, Dhule, Maharashtra, India which was initiated during 2013-2014. The experiment was laid out in randomized block design with eight treatments replicated three times. Treatments for pearl millet composed of T_1: Control, T_2: 100% recommended dose of fertilizer through inorganic fertilizers, T_3: 100 % recommended dose of nitrogen through farm yard manure, T_4: 100 % recommended dose of nitrogen through vermicompost, T_5: 50 % recommended dose of nitrogen through farm yard manure + 50 % recommended dose of nitrogen-through vermicompost, T_6: 5-ton farm yard manure ha^{-1}, T_7: 3-ton vermicompost ha^{-1} and T_8: 2.5-ton farm yard manure ha^{-1} + 1.5-ton vermicompost ha^{-1}). However, treatments for chickpeas are composed of T_1: Control, T_2: 100% recommended dose of fertilizer through inorganic fertilizers, T_3 to T_8: residual effect of farm yard manure, and vermicompost alone and in combinations. The experimental soil was alkaline, calcareous, clayey in texture, low in available nitrogen and phosphorus and high in available potassium. The continuous application of the 100 % recommended dose of nitrogen through farm yard manure for 6 years to pearl millet showed improvement in organic carbon fractions, soil enzyme activity, soil microbial population, and pearl millet equivalent yield. This treatment was followed by the application of 50 % recommended dose of nitrogen through farm yard manure + 50 % recommended dose of nitrogen through vermicompost.

Keywords: *Dehydrogenase, Phosphatase, Soil organic carbon, Urease, Walkley-black, soil microbial biomass, permanganate oxidizable, Humic, Fulvic, Yield.*

INTRODUCTION

Pearl millet, commonly known as bajra is profoundly drought resistant, highly nutritious, and easy to digest cereal grain. Bajra grains are power packed with carbohydrates, essential amino acids, antioxidants properties, and multiple essential minerals *viz;* iron, phosphorus, magnesium, zinc and vitamins *viz;* thiamine, riboflavin, folic acid, niacin, beta carotene. India was the largest producer of pearl millet having area of 76.52 million hectares with production of 108.63 million tonnes and with productivity of 1420 kilograms per hectare during 2020-2021. The major states contributing to this production were Rajasthan (46%), Maharashtra (19%), Gujarat (11%), Uttar Pradesh (8%), and Haryana (6%). In Maharashtra alone, pearl millet was cultivated on 6.88 lakh hectares of land, resulting in a grain production of 6.57 lakh tonnes and a productivity of 955 kilograms per hectare during the same period [1]. Chickpea is an important winter season food legume having grown in crop rotations and 40 per cent of the total pulse production in India [2]. Chickpea cultivation spans approximately 100 million hectares in India, resulting in a total production of 119.1 million tonnes and productivity of 1192 kilograms per hectare. In the state of Maharashtra, chickpea is grown across an area of approximately 20 million hectares, yielding a total production of 17.61 million tonnes and a productivity of 881 kilograms per hectare [3].

Soil organic matter plays a vital role in ecosystem and environmental services [4] as well as in achieving sustainable yields [5]. With the world currently facing the challenge of climate change due to the rapid increase of CO_2 in the atmosphere, the accumulation of soil organic matter and carbon sequestration-has generated attention as a viable option for mitigating climate change on a global scale and at regional levels [6, 7, 8]. Undoubtedly, soil carbon sequestration not only serves as a crucial strategy for climate change mitigation but also holds the potential for enhancing soil fertility and agro-ecosystem

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DOI: https://doi.org/10.58321/AATCCReview.2023.11.04.62

productivity [9,10,11].

The maintenance of soil organic matter was directly linked to the long-term sustainable yield and economic productivity of the cropping system [12]. Extensive fertilizer experiments conducted in various agro-ecoregions of India, encompassing different cropping systems and soil types, revealed a decline in soil organic carbon (SOC) as a result of continuous application of nitrogen fertilizer alone, compared to the application of organic manure [13]. The organic matter introduced into the soil undergoes microbial decomposition, with the intensity of decomposition being influenced by factors such as soil moisture, temperature, and the origin of organic inputs. Numerous studies have highlighted a strong positive correlation between the quantity of carbon integrated into the soil, either through crop residues or external sources like manures [14]. In an ecosystem, the significance of microbial activity in soil processes is to the tune of 80% to 90% [15]. The decomposition of organic matter, nutrient transformation and its availability mainly depend on microbial activity of different microorganisms' habitats in soil and microbial activity is one of the good soil health indicators [16].

Enzymes primarily originate from sources such as soil fungi, bacteria, plant roots, microbial cells, as well as plant and animal residues. They play a crucial role in various biological and biochemical processes, including the degradation of organic matter, the mineralization of litter, and the recycling of nutrients. Enzyme activities are one of the soil quality indicators which are sensitive, rapid, and inexpensive in various metabolic processes in soil [17]. Soil enzymatic activities have important symptoms of soil fertility and microbial functional diversity [18]. Enzymes *viz;* urease and phosphatase are involved in the cycles of N and P for nutrient availability [19].

Considering the paramount importance of soil biological fertility, the long-term field experiment was conducted to study the effect of FYM and vermicompost on soil carbon pools, enzymes and soil microbial activities under pearl millet-chickpea cropping sequence.

MATERIAL AND METHODS

Experimental Site and Soils

The field experiment on “Effect of long-term application of FYM and vermicompost on soil carbon pool, enzymes and microbial activities in Pearl millet-chickpea cropping sequence after 6th crop cycle” was carried out on fixed site at research farm of Bajra Research Scheme, College of Agriculture, Dhule, Maharashtra, India which was initiated during 2013-2014 in Agro climatic Zone-6 *viz*., Scarcity Zone condition of Northern Maharashtra. It lies between 20.4^0N latitude and 74^0 E longitude. The altitude is 258 m above mean sea level. The average annual rainfall received was 730 mm with 45 to 50 rainy days in a year. This is realized entirely by the South-West monsoon.

The initial experimental site was clayey in texture (sand 38.1%, silt 20.2%, and clay 41.7%), medium deep black, alkaline in soil reaction (8.06), low in nitrogen and phosphorous (178 and 11.4 kg ha^{-1}) and high in potassium (254 kg ha^{-1}). Initial status of soil organic carbon fractions were : total organic carbon -106.5 g kg^{-1}, Walkley-black organic carbon - 5264 mg kg^{-1}, water-soluble carbon - 94 mg kg^{-1}, soil microbial biomass carbon - 136 mg kg^{-1}, permanganate oxidizable soil carbon - 152 mg kg^{-1}, particulate organic matter carbon - 754 mg kg^{-1}, humic acid - 8.82 % and fulvic acid - 4.24 %. The initial soil enzymatic activity *viz;* dehydrogenase - 18.34 µg TPF g^{-1} soil 24 h^{-1}, urease - 29.6 mg NH_4-N 100 g^{-1} h^{-1}, alkaline phosphatase - 21.7 µg PNP g^{-1} soil 24 h^{-1} and acid phosphatase - 10.2 µg PNP g^{-1} soil 24 h^{-1}. The initial soil microbial populations were observed: fungi - 7.6 x 10^4 cfu g^{-1} soil, bacteria - 20.8 x 10^7 cfu g^{-1} soil, and actinomycetes - 18.34 x 10^6 cfu g^{-1} soil were found.

Collection and Analysis of Soil Samples

The initial representative soil samples were collected from 0-30 cm depth from the research field. Soil samples were taken after completion of the 6th year trial after harvest of chickpea crop from each treatment by using a core sampler. The soil samples were air dried and pulverized to pass through a 0.5 mm sieve for organic carbon and fresh soil sample were used for estimation of biological properties.

The standard methods were used for soil carbon pools, enzymatic activities, and microbial populations. The total organic carbon (TOC) and Walkley-black organic carbon were determined by TOC analyzer and wet oxidation method [20], the water-soluble carbon (WSC) was determined by water extraction method [21], soil microbial biomass carbon (SMBC) was assayed by chloroform fumigation method [22], the Permanganate oxidizable soil carbon (POSC) was analyzed by permanganate oxidation method [23], the particulate organic matter carbon (POMC) was estimated by wet sieving method [24] and fractions of humic substances (humic and fulvic acid) was investigated by 0.5 *N*NaOHextractant method[25].The enzymatic activities such as dehydrogenase were determined by spectrophotometric method [26], urease activity wasdetermined by titrimetric method[27], and acid and alkaline activities were analyzed by spectrophotometry method [28]. The soil microbial activities *i.e.* fungi, bacteria, and actinomycetes were measured by the serial dilution plate method [29].The data generated in the field experiment was statistically analyzed in a randomized block design [30].

Experimental Details

The long-term field experiment comprised eight different combinations of treatments (Table 1) having plot size 5.00 m x 3.60 m, replicated thrice in a randomized block design. The organic manure *viz.,* FYM and vermicompost were applied in the field as per the treatments ten days before sowing of pearl millet crop every year. The characterization of FYM and vermicompost are given in Table 2. The basal dose of recommended fertilizer (RDF) was applied for pearlmillet (50:25:25 N:P_2O_5:K_2O kg ha^{-1}) and chickpea (25:50:30 N:P_2O_5:K_2O kg ha^{-1}) as per the treatments. The fertilizers, urea, single super phosphate, and muriate of potash were used as a source of N, P, and K, respectively for both pearl millet and chickpea crop in treatment no. 2 (100 % RDF through inorganic fertilizers). For pearl millet, half dose of nitrogen, full dose of P and K was applied at the time of sowing, and the remaining half dose of nitrogen was applied one month after sowing. However, a full dose of N, P, and K was applied at the time of sowing for chickpeas. The crop spacing was 45 cm x 15 cm (row x plant) for pearlmillet and 30 cm x 10 cm (row x plant) for chickpeas. The standard agronomic packages of practices were used in pearl millet-chickpea cropping sequences.

RESULT AND DISCUSSION

Long-term effect of FYM and vermicompost on soil organic carbon fractions.

Total organic carbon

Continuous application of FYM or vermicompost either alone or in combination resulted in a considerable accumulation of total soil organic carbon than absolute control (Table 3). The application of 100 % RDN through FYM recorded significantly higher total organic carbon (151.2 g kg^{-1}) with a 42 % increase over the initial value. The treatments T_4 and T_5 were also independently superior as compared to other treatments. The organically treated treatments were at par with each other. The total organic carbon was in the order of (T_3) 100 % RDN through FYM (151.2 g kg^{-1}) > (T_5) 50 % RDN through FYM + 50 % RDN through vermicompost (133.4 g kg^{-1}) > (T_4) 100 % RDN through vermicompost (127.3 g kg^{-1}) > (T_6) 5 t FYM ha^{-1} (121.6 g kg^{-1}) > (T_8) 2.5 t FYM ha^{-1} + 1.5 t vermicompost ha^{-1} (121.5 g kg^{-1}) > (T_7) 3 t vermicompost ha^{-1} (116.2 g kg^{-1}) > (T_2) 100 % RDF through inorganic fertilizers (110.7 g kg^{-1}) > (T_1) absolute control (98.1 g kg^{-1}). The increase in total organic carbon was 9.1 to 42 % in the treatments of application of FYM or vermicompost either alone or in combination, a 3.9 % increase in the treatment of RDF through inorganic fertilizers and a 7.9 % reduction in the treatment of absolute control over the initial value was observed at the end of 6th cycle of pearl millet-chickpea cropping sequence [31]. Application of organic source as FYM increased organic matter content as compared to only chemical fertilizer this might be due to an increase in shoot and root growth and also a slower and constant rate of mineralization in FYM-treated treatments. Theorganically fertilized plots improved soil organic matter content as compared to the unfertilized plots due to the lower decay rate and higher humification [14].The treatment of 100 % RDF through inorganic fertilizers recorded a total organic carbon of 110.7 g kg^{-1} with only a 3.9 % increase over the initial value, however, the absolute control treatment recorded significantly lower total organic carbon (98.1 g kg^{-1}) with a reduction of 7.9 % over control value. This might be due to less organic carbon in both of these treatments as the above-ground biomass was removed and there was no incorporation of organics or residues in to the soil. The only input of organic matter was through root biomass in these treatments.

Walkley-Black soil organic carbon

The Walkley-Black organic carbon ranged between (T_1) 4884 to (T_3) 8618 mg kg^{-1} in treatment combinations of organic and inorganic fertilizers (Table 3). The Walkley-Black organic carbon content in soil was in the order of (T_3) 100 % RDN through FYM (8618 mg kg^{-1}) > (T_5) 50 % RDN through FYM + 50 % RDN through vermicompost (7414 mg kg^{-1}) > (T_4) 100 % RDN through vermicompost (6932 mg kg^{-1}) > (T_6) 5 t FYM ha^{-1} (6486 mg kg^{-1}) > (T_8) 2.5 t FYM ha^{-1} + 1.5 t vermicompost ha^{-1} (6476 mg kg^{-1}) > (T_7) 3 t vermicompost ha^{-1} (5992 mg kg^{-1}) > (T_2) 100 % RDF through inorganic fertilizers (5492 mg kg^{-1}) > (T_1) absolute control (4884 mg kg^{-1}). The treatments T_4 and T_5 were also independently superior as compared to other treatments. The organically treated treatments were at par with each other for Walkley-Black organic carbon.The increase in the buildup of Walkley-Black organic carbon was 63.71 % in the treatment of 100 % RDN through FYM, 40.84 % in the treatment of 50 % RDN through FYM + 50 % RDN through vermicompost, 31.68 % in the treatment of 100 % RDN through vermicompost. The increase in Walkley-Black organic carbon was more in the treatment 100 % RDN through FYM, which indicated that higher accumulation of organic carbon due to the application of FYM and also due to balanced supply of nutrients resulted in greater input of root biomass due to better crop growth. A similar increase in Walkley-Black organic carbon in the treatments of organic, and treatments inorganic over the absolute control[31]. The reduction in Walkley-Black organic carbon was noted in the treatment of absolute control (T_1) over the initial value.

Water-soluble carbon

A significant increase in the concentration of water-soluble carbon was showed in the treatment of 100 % RDN through FYM (157 mg kg^{-1}) and which-was followed by 50% RDN through FYM + 50% RDN through vermicompost (144 mg kg^{-1}), treatment (T_4) 100% RDN through vermicompost (126 mg kg^{-1}). The application of 100% RDN through vermicompost was at par with application of 5 t FYM ha^{-1} (119 mg kg^{-1}). The treatments T_8,T_7,and T_7,T_2 were at par with each other for water-soluble carbon (Table 3). The higher water-soluble carbon content in the surface layer might be due to the addition of plant residues and microbial activity. Increases in water-soluble carbon (WSC) concentration with the application of FYM have also been reported [32, 33]. Long-term use of FYM and vermicompost form stable soil aggregate and this aggregate contains clay complex which absorb and stores maximum water-soluble carbon [34]. Significantly lower water-soluble carbon (72 mg kg^{-1}) was reported in the treatment of absolute control (T_1).

Soil microbial biomass carbon

The microbial biomass is an essential component of nutrient cycling in the agro ecosystems (Table 3). It is the living component of soil organic matter and it plays a critical role in nutrient cycling and decomposition and transformation of soil organic matter [34]. The soil microbial biomass carbon ranged between 108 to 200 mg kg^{-1} in given treatment combinations. The soil microbial biomass carbon was in the order of T_3>T_5>T_4>T_6> T_8>T_7>T_2>T_1. The increase in soil microbial biomass carbon (SMBC) was 28.7 to 47 % in the treatments of application of FYM or vermicompost either alone or in combination, a 27.2 % increase in the treatment of RDF through inorganic fertilizers and a 20.6 % reduction in the treatment of absolute control over the initial value (136 mg kg^{-1}) was observed at the end of 6th cycle of pearl millet-chickpea cropping sequence. The highest value of microbial biomass carbon in FYM and vermicompost might be due to optimum moisture content, greater soil aggregation, higher soil organic carbon content and higher turn-over of root biomass production. This indicated the activation of microorganisms through carbon source inputs consisting of root biomass and organic residues. Soil organic matter is important substrate for microorganisms which increase in microbial biomass [35]. Soil microbial biomass carbon values were lower without fertilized soils and with chemical fertilizers over to organic manures applied plots [36].

Permanganate oxidizable soil carbon

A significant increase in the concentration of permanganate oxidizable soil carbon was found in application of 100 % RDN through FYM (260 mg kg^{-1}) and followed by treatment of application in 50% RDN through FYM + 50% RDN through vermicompost to pearlmillet (Table 3). The treatments T_4, T_5 and T_6 were at par with each other for permanganate oxidizable soil carbon. The higher values of permanganate oxidizable soil carbon in the treatment of 100 % RDN through FYM, which might be due to the application of FYM as well as higher turnover of root biomass because of better growth and yield of pearl millet and chickpea crops under treatment of FYM as compared RDF and absolute control. Higher variations in permanganate oxidizable organic carbon in this experimentation indicated that this pool of soil organic carbon is more sensitive for change in application of sources of manuring and fertilization. The turn-over of root biomass is greater in application of FYM and vermicompost treatments might be attributed to higher increase in this pool as compared to other remaining treatments

[31]. Significantly lower permanganate oxidizable soil carbon (120 mg kg^{-1}) was observed in treatment T_1 (control) as compared to rest of the treatments at the end of 6th cycle of pearl millet-chickpea cropping sequence.

Particulate organic matter carbon

The concentration of particulate organic matter carbon varied from 503 to 1580 mg kg^{-1} among all the treatments (Table 3). The significant increase in particulate organic matter carbon was observed in 100 % RDN through FYM (1580 mg kg^{-1}) and followed in the descending order of treatment 50% RDN through FYM + 50% RDN through vermicompost (1380 mg kg^{-1}) > 100% RDN through vermicompost (1303 mg kg^{-1}) > 5 t FYM ha^{-1} (1223 mg kg^{-1}) > 2.5 t FYM ha^{-1} + 1.5 t vermicompost ha^{-1} (1193 mg kg^{-1}) > 3 t vermicompost ha^{-1} (1050 mg kg^{-1}). The application of 100 % RDF through inorganic fertilizers recorded the particulate organic matter carbon of 957 mg kg^{-1}. The increase in particulate organic matter carbon was 32.09 to 69.76 % in the treatments of application of FYM or vermicompost either alone or in combination at the end of the 6th cycle of the pearl millet-chickpea cropping sequence. FYM can increase the root biomass and microbial biomass debris which is the main source of particulate organic matter carbon [37].Consistently replenishing the soil with organic manure fosters a conducive setting for carbon cycling and the development of macro aggregates. Moreover, the carbon present in particulate organic matter serves as a binding agent, enhancing the stability of macro aggregates and safeguarding intra-aggregate carbon in the form of particulate organic matter carbon [38, 39].

Humic acid

The application of 100 % RDN through FYM showed the significantly highest concentration of humic acid (14.96 %) and it was followed by the application of 50% RDN through FYM + 50% RDN through vermicompost (14.16 %), 100% RDN through vermicompost (14.01 %) and 5 t FYM ha^{-1} (13.71 %). The treatments T_5, T_4 and T_6 were at par with each other for the concentration of humic acid (Table 4). The treatment of 2.5 t FYM ha^{-1} + 1.5 t vermicompost ha^{-1} (13.12 %), was at par with the 3 t vermicompost ha^{-1} (12.54 %). The increase in humic acid was 42.17 to 69.61 % in the treatments of application of FYM or vermicompost either alone or in combination, a 7.02 % increase in the treatment of RDF through inorganic fertilizers and a 29.59 % reduction in the treatment of absolute control over the initial value (8.82 %) was observed at the end of 6th cycle of pearl millet-chickpea cropping sequence. The plot treated with organic materials exhibited the highest concentration of humic acid. This can be attributed to the decomposition of added residues, which contribute organic substances such as lignin-derived phenolic units, carbohydrates, or amino compounds that serve as the foundational components or substrates for humus formation. Over ten years, the addition of organic amendments resulted in increased organic carbon content and improved crop growth in comparison to the unfertilized control group [40]. Notably, the treatment with absolute control (T_1) reported a significantly lower humic acid level of 6.21%.

Fulvic acid

The concentration of fulvic acid ranged between 2.95 to 7.33 % in different organic and inorganic treatments. The significant increase of fulvic acid (7.33 %) was exhibited in 100 % RDN through FYM (Table 4). The descending order of fulvic acid was present in treatment $T_5>T_4>T_6>T_8>T_7$. The treatment of 100 % RDF through inorganic fertilizers recorded the fulvic acid of 4.80 %. Significantly lower fulvic acid was reported in absolute control (2.95 %). The increase in fulvic acid carbon was 52.59 to 72.87 % in the treatments of application of FYM or vermicompost either alone or in combination, a 13.21 % increase in the treatment of RDF through inorganic fertilizers and a 30.42 % reduction in the treatment of absolute control over the initial value (4.24 %) was observed at the end of 6th cycle of pearl millet-chickpea cropping sequence. The treatments involving organic sources exhibited a greater concentration of fulvic acid compared to both the control group and inorganic treatments. This can be attributed to the consistently higher root biomass observed in these treatments from the beginning of the experiment. The significant increase in organic carbon resulting from the addition of farm yard manure (FYM) can largely be attributed to the higher input of organic materials and direct incorporation of organic matter through FYM. The decomposition of added residues contributes to organic products, such as phenolic units derived from lignin, carbohydrates, and amino compounds, which serve as the building blocks or substrates for humus formation [40].

Long-term effect of FYM and vermicompost on soil enzymatic activities

Dehydrogenase enzyme activity

The dehydrogenase enzyme activity varied widely from 16.47 to 32.77 µg TPF g^{-1} soil 24 h^{-1} among the different treatments (Table 5). The significantly higher dehydrogenase enzyme activities (32.77 µg TPF g^{-1} soil 24 h^{-1}) were observed in the application of 100 % RDN through FYM over to the rest of other treatments. The 50% RDN through FYM + 50% RDN through vermicompost, and 100% RDN through vermicompost were at par with each other in regards to dehydrogenase enzyme activity. The treatment 5 t FYM ha^{-1} (27.07 µg TPF g^{-1} soil 24 h^{-1}), 2.5 t FYM ha^{-1} + 1.5 t vermicompost ha^{-1} (26.73 µg TPF g^{-1} soil 24 h^{-1}) and 3 t vermicompost ha^{-1} (26.27 µg TPF g^{-1} soil 24 h^{-1}) were at par with each other for dehydrogenase enzyme activity. The application of 100 % RDF through inorganic fertilizers recorded the dehydrogenase activity 20.92 µg TPF g^{-1} soil 24 h^{-1} as compared to organic and inorganic fertilizers. The significantly lower dehydrogenase activity (16.47 µg TPF g^{-1} soil 24 h^{-1}) was noticed in the treatment of absolute control. The greater activity of the dehydrogenase enzyme can be attributed to the increased organic carbon content in the soil. This enzyme activity is primarily derived from microorganisms that develop during the decomposition of organic materials. These organic materials serve as a valuable source of carbon and energy for heterotrophs, increasing their population and enzyme activity. The increase in dehydrogenase activity was observed in FYM, vermicompost with N chemical fertilizer. However, the dehydrogenase activity was decreased to the tune of 10.2 % in the treatment of absolute control over the initial value (18.34 µg TPF g^{-1} soil 24 h^{-1}) at the end of the 6th cycle of pearlmillet-chickpea cropping sequence. The more pronounced impact of farmyard manure (FYM) on dehydrogenase activity could be attributed to the easier decomposition of organic matter and the subsequent increase in microbial growth facilitated by the addition of carbon substrates [41].The application of organic manures increase the total porosity in soil and is ultimately found to have higher dehydrogenase activity [42].

Urease enzymatic activity

The urease enzyme activity ranged from 22.17 (T_1) to 54.98 (T_3) mg NH_4-N 100 g^{-1} soil h^{-1}(Table 5). The urease enzyme activity was in the order of (T_3) > (T_5) > (T_4) > (T_6) > (T_8) > (T_7) > (T_2) >

(T_1). The increase in urease enzyme activity was 27.7 to 85.7 % in the treatments of application of FYM or vermicompost either alone or in combination, 10 % increase in the treatment of RDF through inorganic fertilizers and 25.1 % reduction in the treatment of absolute control over the initial value (29.6 mg NH_4-N 100 g^{-1} soil h^{-1}) was observed at the end of 6thcycle of pearl millet-chickpea cropping sequence. The higher soil urease activity was found only in organic applied sources of nutrient treatment could be attributed to their C:N ratio, greater N inorganic sources found higher decomposition and better mineralization [43].

Alkaline phosphatase activity

The alkaline phosphatase activity ranged between 11.32 to 47.84 µg PNP g^{-1} soil 24 hr^{-1} in organic and inorganic treatments (Table 6). A significant increase in alkaline phosphatase activity was observed in the treatment of 100 % RDN through FYM (47.84 µg PNP g^{-1} soil 24 hr^{-1}). The treatment $T_3$and T_5 were at par with each other in respect to alkaline phosphatase activities. The 100% organically treated treatment *i.e.* T_6, T_7 and T_8 were at par with each other. The increase in alkaline phosphatase activity was 45.7 to 120.5 % in the treatments of application of FYM or vermicompost either alone or in combination, 18.1 % increase in the treatment of RDF through inorganic fertilizers and a 47.8 % reduction in the treatment of absolute control over the initial value (21.7 µg PNP g^{-1} soil 24 hr^{-1}) was observed at the end of 6th cycle of pearl millet-chickpea cropping sequence. The increased microbial activity, potentially accompanied by a greater diversity of phosphate-solubilizing bacteria resulting from the long-term application of manure, contributes to the significantly higher alkaline phosphatase activities observed in the soils treated with farmyard manure (FYM) [44].The alkaline phosphatase activity was highly influenced the due increase in microbial biomass carbon, and optimum and balanced application of fertilizers [45]. The alkaline phosphatase activity surpassed the acid phosphatase activity in all treatment groups, which can likely be attributed to the alkaline nature of the soil (pH 8.06) in this particular experiment.

Acid phosphatase activity

The acid phosphatase activity was lowest (7.25 µg PNP g^{-1} soil 24 hr^{-1}) and highest (22 µg PNP g^{-1} soil 24 hr^{-1}). The application of 100 % RDN through FYM was significantly higher in acid phosphatase activity as compared to the rest of other treatments (Table 6). The treatments $T_3$and T_5 were at par with each other in respect to acid phosphatase activities. The combination of inorganic and organically treated treatments *i.e.* T_4, T_5, and T_6 were at par with each other. The increase in acid phosphatase activity was noted in the treatments of application of FYM or vermicompost either alone or in combination as compared to RDF at the end of the 6th cycle of the pearl millet-chickpea cropping sequence. The acid phosphatase activity was positively influenced due increase in microbial biomass carbon, and optimum and balanced application of fertilizers [45].

Long-term effect of FYM and vermicompost on soil microbial populations.

Bacterial Population

The application of 100 % RDN through FYM has recorded a significantly higher bacterial population (48.03 x 10^7cfu g^{-1}soil) as compared to the rest of all other treatments (Table 7).The lower bacterial population (18.50 x 10^7cfu g^{-1} soil) was observed in the control treatment. In the case of the bacterial population at pare result was observed between treatment T_3 and T_5. The treatments T_4, T_5, T_6 and were at par with each other. The higher bacterial population was observed in the treatments of application of FYM or vermicompost either alone or in combination over the initial values at the end of the 6th cycle of the pearlmillet-chickpea cropping sequence. The higher bacterial population was observed in addition to organic inputs such as FYM and vermicompost, this might be due to the addition of carbon and improved soil properties and soil quality. The application of organic manure stimulates the growth and activities of soil microorganism ultimately increase its population in the soil [46]. The different crop roots secretion of various types of organic acids, which is a readily available source as energy for soil microorganisms [47].

Fungal Population

The significantly lower fungal count (5.70 x 10^4cfu g^{-1}) was noticed in treatment T_1 and the highest in treatment T_3 (15.57 x 10^4cfu g^{-1}). The treatment T_4, T_6 and T_8 were at par with each other (Table 7). The treatment T_8, T_7 and T_2 were at par with each other. The increase in fungal count was 12.2 to 104.8 % in the treatments of application of FYM or vermicompost either alone or in combination, a 2.6 % increase in the treatment of RDF through inorganic fertilizers and 25 % reduction in the treatment of absolute control over the initial value (7.6 x 10^4cfu g^{-1} soil) was observed at the end of 6th cycle of pearl millet-chickpea cropping sequence. The application of FYM or vermicompost treatments exhibited higher fungal populations probably may be greater bioavailability of growth-promoting substances. Similar results were close in conformity with [45]. The application of the recommended dose of fertilizer led to lower microbial population levels compared to the organic manure treatments, yet these levels were significantly higher than those observed in the control treatment.

Actinomycetes Population

The actinomycetes population was relatively lower than the bacterial population and higher than fungal population in this experiment study (Table 7). The actinomycetes population was ranged between 14.03 to 41.50 x 10^6cfu g^{-1}soil among all the treatments. The application of 100 % RDN through FYM was recorded as significantly greater in the actinomycetes population. The combination of organic and inorganic treatments T_3, T_4 and T_5 were at par with each other. The organically treated treatments T_6, T_7 and T_8were at par with each other. The increase in actinomycetes population was 33 to 99.5 % in the treatments of application of FYM or vermicompost either alone or in combination, a 4.3 % increase in the treatment of RDF through inorganic fertilizers and a 32.5 % reduction in the treatment of absolute control over the initial value (20.8 x 10^6cfu g^{-1} soil) was observed at the end of 6th cycle of pearl millet-chickpea cropping sequence.The population of actinomycetes was found to increase with the application of organic manures such as farmyard manure (FYM) and vermicompost. This can be attributed to the enhancement of soil organic matter quality by FYM and vermicompost, which in turn indicates the soil's capacity to store and recycle nutrients and energy. The increase in actinomycetes biomass exhibited a proportional relationship with the addition of nutrients, stimulating microbial activity [45].

Long-TermEffect ofFYMand Vermicompost onYield of Pearlmillet-Chickpea

Grain and Stover yield of pearl millet

The grain yield of pearl millet ranged between 13.33 to 25.01 q ha^{-1} (Table 8). The significantly higher grain yield (25.01q ha^{-1}) and stover yield (36 q ha^{-1}) of pear millet were noticed in the application of 100 % RDN through FYM as compared to rest of the other fertilizer treatments. The treatments T_5,T_4,T_2,T_8, T_6, and T_7 were found at par with the treatment T_3 for grain and stover yield of pearlmillet. The grain and stover yield attributes were significantly increased in long term application of FYM and vermicompost and inorganic fertilizer. The increase in pearl millet yield might be due to increase in beneficial microbial biomass, mineralization of essential nutrient there by increased nutrient availability and absorption by pearl millet ultimately increase in yield. The findings revealed that the application of farmyard manure (FYM) at 100% recommended dose of nitrogen (RDN) resulted in the highest grain yield for pearl millet. This can be attributed to the maximum availability of plant nutrients in this treatment, which contributed to a more optimal source-sink relationship. This indicates that a greater amount of dry matter or photosynthates produced by the source organs were effectively translocated towards the sink organs, specifically the economic part of the plant, leading to a higher grain yield [48]. The significantly lower grain yield (13.33 q ha^{-1}) and stover yield (22.11 q ha^{-1}) of pearl millet was exhibited in absolute control, however, treatment T_1 was at par with the treatments T_6, T_8 and $T_7$for stover yield of pearl millet. Similar results were close in conformity with [49, 50].

Grain and straw yield of chickpea

The significantly superior grain yield (18.63 q ha^{-1}) and straw yield (28.69 q ha^{-1}) of chickpeas were noticed in the residual effect of treatment T_3 (100 % RDN through FYM) over the remaining treatments (Table 8). All the treatments were at par with each other for grain and straw yield of chickpeas except T_1. However, the significantly lower grain yield (12.74 q ha^{-1}) and straw yield (18.35 qha^{-1}) of chickpea was reported in the treatment (T_1) absolute control. The treatment T_1 was at par with the treatments T_4, T_6, $T_7$and T_8 in respect of grain and straw yield of chickpea. The results showed that the planting of chickpeas after pearl millet on the residue of (T_3) 100 % RDN through FYM produced significantly higher chickpea grain and straw yield due to the better residue of nutrients available under T_3 and better nutrient absorption by chickpea and The production of photosynthates by the source organs and their subsequent translocation towards the sink organ, specifically the economic part, resulted in an increased grain yield of chickpea [48]. The application of FYM or vermicompost alone or combination were found better residual effect on grain and straw yield of chickpea [51].

Equivalent yield of pearl millet in pearl millet –chickpea cropping system

The soil application of 100 % RDN through FYM to pearl millet and its residual effect on chickpea exhibited a significantly higher value of equivalent yield (65.38 q ha^{-1}) of pearl millet over the rest of the organic alone and combination of chemical fertilizers (Table 8). Treatment of soil application of 100 % RDN through FYM to pearl millet and its residual effect on chickpea was at par with the treatments (T_5) 50% RDN through FYM + 50 % RDN through vermicompost (63.70 q ha^{-1}), (T_2) 100 % RDF through inorganic fertilizers (61.30 q ha^{-1}), (T_4) 100 % RDN through vermicompost (59.60 q ha^{-1}) and (T_6) 5t FYM ha^{-1}(54.32 q ha^{-1}). The equivalent yield of pearl millet was higher in the treatment of 100 % RDN through FYM, as the long-term application of FYM improved in organic carbon fractions, soil enzyme activity, soil microbial population which effects on physical, chemical and biological soil properties and resulted in higher soil fertility and soil productivity. The chickpea sown in winter after pearl millet in successive manner for residual effect different organic source such as FYM and vermicompost as well as chickpea legume crop gets additional benefit for increasing in equivalent yield of pearl millet. The treatment without fertilizer obtained lower pearl millet equivalent yield (40.93 q ha^{-1}) and it was at par with the treatmentsT_7 and T_8.

CONCLUSION

The soil application of 100% recommended dose of nitrogen through FYM for upto 6 years were found better increment in organic carbon fractions, soil enzyme activity, soil microbial population, and pearl millet equivalent yield, which was followed by the application of 50 % recommended dose of nitrogen through FYM + 50 % recommended dose of nitrogen through vermicompost in pearl millet-chickpea in intensive cropping sequence.

FUTURE SCOPE

Studying the long term effects of FYM and Vermicompost in a cropping sequence after multiple cycles can contribute significantly to advancing sustainable agricultural practices, and enhancing soil health, while addressing key environmental challenges such as climate change and biodiversity loss.

ACKNOWLEDGMENTS

I sincerely express my gratitude and indebtedness for the Bajra Research Scheme, College of Agriculture, Dhule for providing the necessary facilities for conducting the long term experiment.

AUTHORS' CONTRIBUTION STATEMENTS

Prasad B. Margal executed the field research and laboratory analysis, Dr. Vikrant P. Bhalerao worked as the research guide and chairman of the students advisory committee, and Dr. Bhimrao M. Kamble worked as member of the students advisory committee, while Dr. Ritu S. Thakare is helped in improving the manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

Table1.Treatment details.

Treatment No.	Pear millet	Chick Pea
T_1	Control	Control
T_2	100 % RDF through inorganic fertilizers	100 % RDF through inorganic fertilizers
T_3	100 % RDN through FYM	Residual effect
T_4	100 % RDN through vermicompost	Residual effect
T_5	50 % RDN through FYM + 50 % RDN through vermicompost	Residual effect
T_6	5 ton FYM ha^{-1}	Residual effect
T_7	3 ton vermicompost ha^{-1}	Residual effect
T_8	2.5 ton FYM ha^{-1} + 1.5 ton vermicompost ha^{-1}	Residual effect

Table2.Characterization of FY Man vermicom post organic sources.

Sr. No.	Parameters	FYM	Vermicompost
1.	pH	7.08	6.78
2.	EC(dS m^{-1})	0.51	0.63
3.	OrganicC(%)	14.9	21.48
4.	TotalN(%)	0.62	1.14
5.	TotalP (%)	0.39	0.88
6.	TotalK(%)	0.64	1.07
7.	C:Nratio	24.03	18.84

Table 3. Long term effect of FYM and vermicompost on soil organic carbon pools.

Treatment No.	Total organic carbon (gkg^{-1})	Walkley–Black soil organic carbon (mgkg^{-1})	Water soluble carbon (mgkg^{-1})	Soil micro bialbio mass carbon (mgkg-1)	Permanganate oxidizable Soil carbon (mgkg^{-1})	Particular organic matter Carbon (mgkg^{-1})
T_1	98.1^{g}	4884^{g}	72^{g}	108^{d}	120^{e}	503^{g}
T_2	110.7^{f}	5492^{f}	102^{f}	173^{c}	168^{d}	957^{f}
T_3	151.2^{a}	8618^{a}	157^{a}	200^{a}	260^{a}	1580^{a}
T_4	127.3^{c}	6932^{c}	126^{c}	193^{a}	213^{bc}	1303^{c}
T_5	133.4^{b}	7414^{b}	144^{b}	197^{a}	230^{b}	1380^{b}
T_6	121.6^{d}	6486^{d}	119^{cd}	183^{b}	197^{bcd}	1223^{d}
T_7	116.2^{e}	5992^{e}	107^{ef}	175^{bc}	176^{d}	1050^{e}
T_8	121.5^{de}	6476^{d}	112^{de}	180^{bc}	187^{cd}	1193^{d}
SE±	1.80	136	2.44	3.22	11.6	25.11
CD (0.05)	5.39	412	7.39	9.80	35.22	76.36

The same letters in a column are not different at the 0.05 probability level.

Table 4. Long term effect of FYM and vermicompost on humic and fulvic acid substances.

Treatment No.	Humicacid (%)	Fulvicacid (%)
T_1	6.21^{e}	2.95^{g}
T_2	9.44^{d}	4.80^{f}
T_3	14.96^{a}	7.33^{a}
T_4	14.01^{b}	6.97^{bc}
T_5	14.16^{b}	7.21^{ab}
T_6	13.71^{b}	6.75^{cd}
T_7	12.54^{c}	6.47^{e}
T_8	13.12^{c}	6.68^{de}
SE±	0.19	0.08
CD (0.05)	0.58	0.26

The same letters in a column are not different at the 0.05 probability level.

Table 5. Long term effect of FYM and vermicompost on dehydrogenase and urease soil enzyme.

Treatment No.	Dehydrogenase (μgTPFg^{-1} soil 24 h^{-1})	Urease (mgNH$_4$-N100 g^{-1} soil h^{-1})
T_1	16.47^{d}	22.17^{e}
T_2	20.92^{c}	32.56^{d}
T_3	32.77^{a}	54.98^{a}
T_4	28.87^{ab}	40.25^{bc}
T_5	29.28^{ab}	42.00^{b}
T_6	27.07^{b}	39.67^{bc}
T_7	26.27^{b}	37.80^{c}
T_8	26.73^{b}	38.97^{bc}
SE±	1.36	1.37
CD (0.05)	3.92	4.16

The same letters in a column are not different at the 0.05 probability level.

Table 6. Long term effect of FYM and vermicompost on acid and alkaline phosphatase soilenzyme.

Treatment No.	Alkalinephosphatase (μgPNPg^{-1}soil 24 hr^{-1})	Acidphosphatase (μgPNPg^{-1}soil 24 hr^{-1})
T_1	11.32^{e}	7.25^{f}
T_2	25.63^{d}	12.18^{e}
T_3	47.84^{a}	22.00^{a}
T_4	38.56^{b}	19.58^{bcd}
T_5	45.41^{a}	21.24^{ab}
T_6	34.31^{c}	19.82^{bc}

T_7	31.62^{c}	17.96^{d}
T_8	33.81^{c}	18.90^{cd}
SE±	1.007	0.57
CD (0.05)	3.056	1.73

The same letters in a column are not different at the 0.05 probability level.

Table 7. Long term effect of FYM and vermicompost on soil microbial populations.

Treatment No.	BacterialPopulation (x 10^{7}cfug^{-1} soil)	FungalPopulation (x 10^{4}cfug^{-1} soil)	Actinomycetes Population (x 10^{6}cfug^{-1} soil)
T_1	18.50^{e}	5.70^{e}	14.03^{f}
T_2	26.83^{d}	7.80^{d}	21.70^{e}
T_3	48.03^{a}	15.57^{a}	41.50^{a}
T_4	41.70^{bc}	10.37^{c}	35.17^{abc}
T_5	44.93^{ab}	13.10^{b}	38.00^{ab}
T_6	41.27^{bc}	10.07^{c}	32.00^{bcd}
T_7	40.00^{c}	8.53^{d}	27.67^{de}
T_8	40.48^{bc}	9.17^{cd}	29.83^{cd}
SE±	1.50	0.45	2.11
CD (0.05)	4.54	1.39	6.39

The same letters in a column are not different at the 0.05 probability level.

Table 8. Long term effect of FYM and vermicompost on pearl millet and chickpea yield.

Treatment No.	Pearl millet yield (qha^{-1})		Chickpea yield (qha^{-1})		Pearl millet equivalent yield (qha^{-1})
	Grain	Stover	Grain	Straw	
T_1	13.33^{b}	22.11^{b}	12.74^{b}	18.35^{b}	40.93^{b}
T_2	22.97^{a}	33.16^{a}	17.69^{ab}	26.54^{a}	61.30^{a}
T_3	25.01^{a}	36.00^{a}	18.63^{a}	28.69^{a}	65.38^{a}
T_4	22.14^{a}	33.67^{a}	17.29^{ab}	25.59^{ab}	59.60^{a}
T_5	24.44^{a}	35.63^{a}	18.12^{ab}	27.54^{a}	63.70^{a}
T_6	19.93^{ab}	30.76^{ab}	15.87^{ab}	23.33^{ab}	54.32^{a}
T_7	17.92^{b}	30.01^{ab}	14.30^{ab}	20.72^{b}	48.90^{b}
T_8	19.17^{ab}	31.43^{a}	14.97^{ab}	21.86^{ab}	51.61^{b}
SE±	2.28	2.99	1.82	2.43	4.08
CD (0.05)	6.92	9.02	5.48	7.32	12.36

The same letters in a column are not different at the 0.05 probability level.

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