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Effects of Subsoiling and Organic Amendments on Selected Soil Physicochemical Properties and Sugar Yield in Metahara Sugar Estate

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Abstract: Sugar industry residues such as filter cake and vinasse often available at a very close distance, with minimum cost and subsoiling, can be used to improve and sustain soil physicochemical properties and in turn to ameliorate compaction effects of Ethiopian Sugar Estate soils. This field experiment was conducted in 2016 on light soil management unit group at Metahara Sugar Estate with the objective of assessing the effects of different rates and types of organic amendments and subsoiling on some physicochemical properties of soils. Field experiment was laid in a randomized complete block design and replicated three times. Four levels of filter cake (0, 15, 30, 45 t ha^{-1}), four levels of compost (0, 11.03, 22.07, 35.86 t ha^{-1}) and four levels of vinasse (0, 35, 70, 105 m^3 ha^{-1}) in combination with subsoiling operation at a depth of 70 cm with 91 cm shank distance were studied as treatment combinations at Metahara Estate. The results of the study revealed that maximum bulk density and penetration resistance were recorded for the control plots. It was observed that minimum bulk density and penetration resistance values were recorded in plots that were subsoiled. Higher concentration of soil organic carbon, available P and total N were observed in plots that received organic amendments. The maximum sugar yield (18.95 t ha^{-1}) was recorded in subsoiled plots followed by the treatment that have filter cake compost rate of 22.07 t ha^{-1}. Therefore, it can be concluded that depth targeted and site specific subsoiling operation can be used when there is any problem related to compaction and severe plough pan within the underlying soil layers, which could cause restricted root growth. Moreover, soil compactibility due to use of heavy machinery during sugarcane production can be reduced by incorporating 30 and 22.07 t ha^{-1} filter cake and filter cake compost sugarcane residues, respectively, before Magnum case III 315 tractor passes. There is a need for further study with different dose of the residues on soil management unit groups of the other estate soils and Metahara heavy soil management unit.

Key words: Improvement Measures · Filter Cake · Vinasse · Filter Cake Compost · Subsoiling

INTRODUCTION

Sugar industry development in Ethiopia was initially started in Wonji-Shoa in 1954. Nearly 60 years since the industry started in an organized manner, four small to medium sized sugar factories with a combined daily crushing capacity of about 12, 500 tons were installed in 3 separate locations across the country. The increase in sugarcane and sugar production has inevitably resulted in increased quantity of waste products. The major waste products from sugar processing and alcohol manufacture are bagasse from the cane crushing operation, filter cake from the cane juice filtration, molasses and vinasse from distilleries. The sugarcane industry in Ethiopia, in

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combined form, producing a large amount of sugarcane by-products, amounting to about 7.8 x 10^5 tonnes of bagasse, 7 x 10^4 tonnes of filter cake, 9.8 x 10^4 tonnes of mollasses and 3.3 x 10^6 m^3 of vinasse, in the year 2012/2013 [1].

A significant proportion of these industrial wastes are returned to nearby fields as soil conditioners or low concentration fertilizer but many factories are left with huge surpluses of filter cake and vinasse which have to be dumped on specially allocated sites because the high transport and spreading costs of the by-products cannot be justified for distant fields [2]. From environmental point of view, these by-products are known to have no side effects when disposed to farmlands [3]. However, when industrial waste is applied at higher doses, it could affect permeability and infiltration rate of the soils besides causing environmental pollution [4].

Sharp rises in the price of mineral fertilizers necessitates the more economically integrated use of organic and mineral fertilizer resources [5]. Numerous workers have reported the beneficial effects of filter cake, vinasse and filter cake compost [6] on the chemical and physical properties of soils. The potential advantages of composting filter cake are; for the production of a marketable product, reduction of environmental pollution by solid waste, weight reduction of the filter cake as a result of drying and decomposition of organic matter and increase in the nutrient concentration in the filter cake due to the removal of water and cellulose [7].

In the rapid mechanization of farm operations, long term use of the same implements when soils are cultivated repeatedly at the same depth with low amount of organic additives could lead to subsoil compaction, which ultimately affects soil properties. Plow pan (Tillage-induced compaction layer) occurs in the layer of soil just below the depth of tillage [8]. Subsoiling is only a way to loosen up a compacted soil and do not serve as a protection. It is important to recognize that using subsoiling is only a short-term solution to soil compaction and is very expensive. If compactions by machines are prevented by controlled wheel traffic the effects of subsoiling could last for three years [9].

Ultimately in the long term, agronomic practices must be adopted to minimize wheel traffic compaction. The easiest way to prevent soil damages is to avoid all operations when the soil moisture content is high. Moreover, Filter cake, vinasse and their compost have been used successfully to reduce the effect of soil compaction [10]. Moreover, incorporation of organic matter increases electric charge, thus, increasing repulsive forces between soil particles and improves soil aggregate strength and in turn increases the capacity of soil to resist external effort [11].

The importance of organic matter in reducing soil compactibilty of soils under sugarcane was recognized [12]. However, a survey of the literature showed how few studies have quantified the effects of subsoiling and different organic materials on the physicochemical properties of soils compared with other factors affecting compaction, such as texture, soil water content and compactive effort. By-products of sugarcane have been shown to be a valuable source of organic matter. Moreover, in Ethiopia sugarcane by-products and subsoiling have been used for sugar plant cultivation since long time. Some Ethiopian Sugar Estates (e.g. Metahara and Wonji-Shoa) are already using these organic materials and subsoiling in an attempt to improve their soil fertility status and sugarcane plant growth and for loosening effect of compacted soils.

Studies carried out in the estates indicated that combined use of filter cake and vinasse with mineral fertilizers resulted in positive effect on sugar yield [13]. Currently, increasing cost of mineral fertilizers besides high need to increase productivity of fields makes knowledge on the use of such by-products for agricultural purpose an important approach to ensure sustainable sugarcane production in the country. However, there is no study made on the optimum rate of organic amendments, better types of improvement measures including subsoiling and their effect on soil properties and cane yield with respect to soil compaction. Therefore, this study was conducted with the objective of assessing the effects of different rates and types of organic amendments and subsoiling on selected physicochemical properties of soil.

MATERIALS AND METHODS

General Description of the Study Areas: The study was conducted at Metahara Sugar Estate which is located at about 200 km southeast of Addis Ababa in the central part of the East African Rift Valley system at 8° 45' 4.16?? to 8° 53' 20.75?? N and 39° 49' 10.74?? to 40° 0.21' 1.48?? E. It has a semi arid climatic condition (Figure 1). The total area under cultivation is about 10, 248 ha with an average cane yield of 165 t ha^{-1} [14] (Figure 1).

The study area is characterized by diverse physiogeographic features. The slope of the field is generally very gentle and regular which makes them suitable for gravity irrigation [15]. The Estate is found at

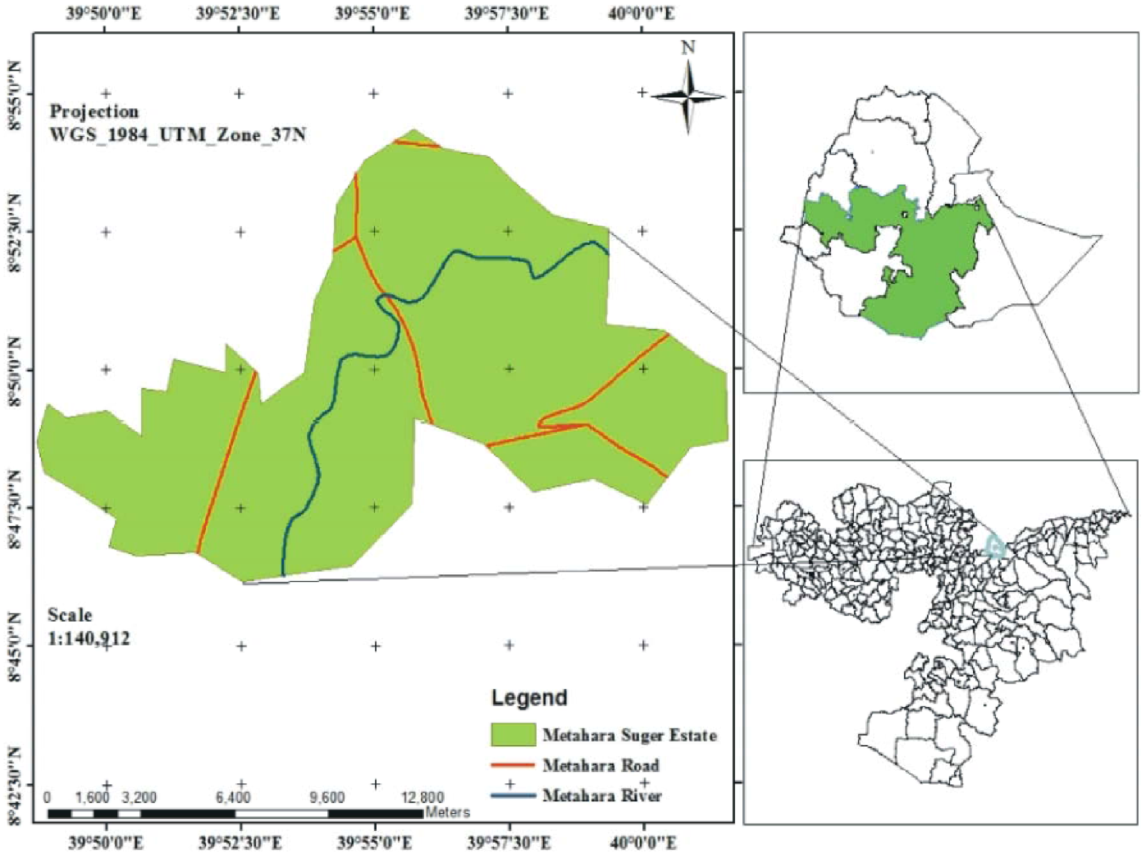

Fig. 1: Location Maps of the Metahara Sugar Estate in Ethiopia

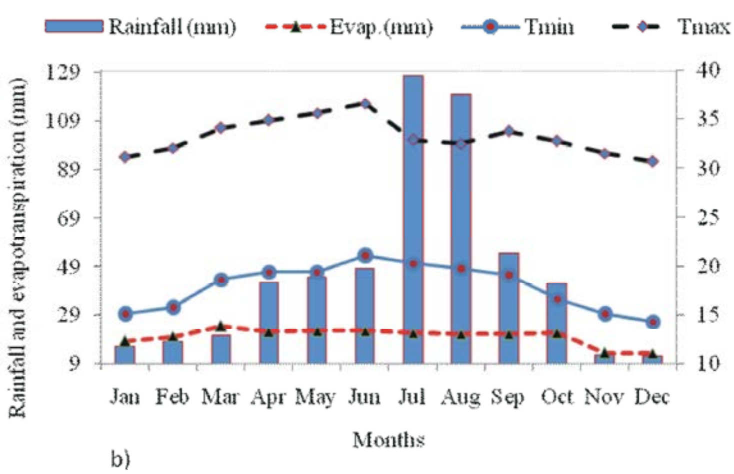

Fig. 2: Ten years mean monthly rainfall, evapotranspiration (Evap) and monthly minimum (Min) and maximum (Max) temperatures of Metahara Estate

altitude of 950 meter above sea level in the Awash River Basin. The mean annual rainfall in the study area is 539.39 mm. Ten years (2003-2013) climatic data (Figures 2) of the Metahara Estate indicated that the areas have a bimodal rainfall pattern in which small rain is received from February to April, while the main rainy season that contributes a significant proportion of the total annual rainfall is received during June to September. Average minimum and maximum temperatures of the estate are about 17.73 and 33.24 °C [16].

Majority soils of Metahara Estate is developed under tropical hot condition from alluvium-colluvium parent materials which include basic volcanic rocks such as (Basalt, limestone), acidic volcanic rocks such as (Granite, sandstone) as well as recent and ancient alluvial soils [17]. Soils of Metahara Estate are classified as Calcaric Cambisols [18]. Moreover, the estate is grouped into a total of six soil management units. This grouping of soil management approach was adopted from Kuipers [19] though there is no documented information concerning depth of sampling, number of samples and methods of sampling for $pF_{2.0}$ soil management classification of the estate. The first three soil groups (Class-$_4$, Class-$_5$ and Class-$_{6)}$ of the estate are heavy textured soils; while the last three soil types (Class-$_{1,}$ Class-$_2$ and Class-$_3$) are light textured soils [20]. Furthermore, the light textured soils require frequent but light irrigation, while the heavy textured ones require less frequent but heavy irrigation [21].

In Metahara Estate, along with the cane plantation, the enterprise owns 140 ha of land covered with various types of fruits such as oranges, mangoes, lemons, grapefruits, etc. About 3, 000 tonnes of fruits are produced annually. The average land productivity of the estate is about 165 tonnes of cane per hectare. These make the Ethiopian Sugarcane plantation farms one of the highest cane producing farms in the world [22]. Planting of seedlings and transplantation of sugarcane is done manually but cultivation and chemical spraying are accomplished mechanically. Tillage operations such as uprooting, subsoiling, plowing, harrowing, labeling and furrowing are conducted before planting cane sets. Mechanization is also used for other farm operations like cane loading and cane haulage. Planting of sugarcane is usually practiced from mid-October to the end of June in a particular year. Sugarcane is planted at a rate of 16-18 t/ha in the estate [23]. The most widely used fertilizer in the study area is ammonium sulfate nitrate (26% N) with the application rates of 300 kg ha^{-1} for planting sugarcane, 500 kg ha^{-1} for the second and third cuttings and 650 kg ha^{-1} for the fourth and subsequent cuttings [24].

Site Selection, Experimental Design and Procedures: Field experiment was conducted at Metahara Sugar Estate, Awash section on a soil representing the light soil management unit group. The experimental field was selected based on the available pF_2 soil map, harvesting scheme and on previous yield history of the field (Free of drainage and salinity problems) in consultation with the Metahara research station and sugarcane plantation department offices.

The experiment was laid down in a randomized complete block design with three replications. Land preparation was done as per the actual land preparation procedures of Metahara Estate. After randomized complete block design lay out measurement, air dried filter cake at four levels (0, 15 (FC_1), 30 (FC_2), 45 (FC_3) t ha^{-1}), four levels of filter cake compost (0, 11.03 (com_1), 22.07 (com_2) and 35.86 (com_3) t ha^{-1}) and four levels of vinasse (0, 35 (V_1), 70 (V_2) and 105 (V_3) $m^3.ha^{-1}$) were manually applied in combination with subsoiling operation at a depth of 70 cm with 91 cm shank distance as treatment combinations. Filter cake and vinasse samples were collected from Metahara Sugar Factory and filter cake compost was prepared at Metahara Windrow composting field.

The rates of amendments were selected based on the rates recommended by Girma Abejehu [25] and being used presently by some of the Ethiopian Sugarcane Estates (30 $t.ha^{-1}$ of filter cake and 70 $m^3.ha^{-1}$ of vinasse, respectively). Liquid vinasse was manually applied using 20 l plastic container. The field was irrigated up to saturation using irrigation mechanism of the Estate. To prevent mixing of treatments between plots, each plot was irrigated separately by closing furrow ends (Dike). According to calibrated days for moisture levels on 8th day after irrigation, soil compaction was imposed. Compaction was induced using tractor to simulate the responses of selected soil properties of the Estate to different soil amendments before compaction and deep tillage after compaction. Model Magnum case III - 315 tractor with 12 tonne mass (The model widely used and with maximum mass of all tractors used at Metahara Estate) was passed through each plot of the field 12 times uniformly to and fro at a speed of 5.6 km hr^{-1} for all treatments.

Four weeks after applying compaction, deep ploughing was applied to three plots up to the depth of 70 cm. After furrow and dike reshaping and soil sampling were completed, sugarcane was planted on the back ground. Planting was executed using healthy two budded equal number of setts of test variety (NCO 334). After planting, the setts were covered with soil immediately and each plot was irrigated lightly. Then, the plots were irrigated separately. After three months, furrow ends of each plot were opened and the usual irrigation activity was made to continue as per the practice of the Metahara Estate. Water was applied by furrow irrigation (Using hydroflume), which is a popular method for 80% of Metahara sugarcane production. The plots consisted of 4 furrows, each 15 m length, 1.45 m width and the spacing between two consecutive plots was 2.9 m.

The area of single experimental plot was 87 m^2 and the spacing between two consecutive plots was 2.9 m (Double furrow). Molding and fertilization were done manually to avoid additional stress.

Eight months after applying compaction and improvement measures [26] composite and core samples were collected and measurement of penetration resistance was done per each plot. Penetration resistance was measured using a manually operated soil cone penetrometer [27] with a cone base diameter of 11.28 mm and 15.96 mm with cone angle of 30°. The cone was hand-pushed into the soil at a uniform rate of 2 cm/sec [28] eight months after imposing treatments. Penetration resistance measurements were taken from the center of tyre truck at 10 cm increments to a depth of 60 cm. Six penetration resistance measurements were taken in each plot and the parallel values at each depth were expressed as an average. For windrow system of composting of filter cake and vinasse, the approach proposed by Mahamuni and Patil [29] was adopted.

Soil Sampling and Preparation for Laboratory Analysis: To determine soil physicochemical properties of study area composite and undisturbed soil samples were drawn from top layer (0 to 30 cm) and subsoil layer (30 to 60 cm) of each experimental plot before and after planting. Prior to sugarcane planting, soil sample was collected by auger from eleven plots and thoroughly mixed to make one composite sample per each block from both layers. A total of three composite samples were collected from the three blocks per each layer. At the same time, one undisturbed core sample per block from both top and subsoil layers were also randomly collected using core method to determine soil bulk density (Table 1).

For soil sampling after applying treatments from each plot an auger was used to sample five randomly selected spots per plot from both top and subsoil layers. These five subsample soils from each layer combined into one composite soil sample per each plot for investigating soil properties. Similarly, undisturbed core samples from both layers was also collected to determine soil bulk density of each plot. Eight months after applying treatments, 66 core samples (5 cm height and 5 cm diameter) and 66 composite samples from 0-30 cm and 30-60 cm depth of 33 experimental plots were collected. About 1 kg of the composite soil samples of each were taken and placed in a polyethylene tube labeled with the required information and transported to Metahara research station and Wonji central laboratory. In the laboratory, the collected composite soil samples were air-dried, ground and sifted to pass through a 2 mm sieve except 0.5 mm sieve for analysis of soil organic carbon and total nitrogen.

Laboratory Analysis of Soils: Soil samples that were collected from each plot eight months after applying treatments were analyzed for selected soil physical and chemical properties. The soil samples were subjected to laboratory analysis to determine selected soil physical properties (Bulk density, total porosity and soil moisture content) and chemical properties (Soil pH, soil organic carbon, total N and soil available P). Bulk density was computed from the values of oven dry soil mass and volume of core sample as described by Jamison *et al*. [30]. Particle density of the soils was determined using the pycnometer method following the procedure described in Rao [31]. Total porosity was calculated from the values of bulk density and particle density using the method described by Rowell [32]. The soil moisture in the samples was also determined gravimetrically as described by Reynolds [33].

Soil pH was determined in soil to water ratio of 1:2.5 by glass electrode pH meter [34]. Organic carbon was determined using the wet digestion and oxidation method as described by Walkly and Black [35]. Total N content in the soils was determined using the Kjeldahl procedure [36]. Soil available phosphorus was determined according to the Olsen's method [37] except for Finchaa Estate where Bray II extraction method was used for soils with pH < 6 [38]. The P extracted with different methods was measured by spectrophotometer following the procedures described by Murphy and Riley [39]. The result of soil analysis for prior to sugarcane planting is presented in Table 2 below.

Chemical analysis of filter cake compost, filter cake and vinasse: Filter cake compost was done from the filter cake and vinasse collected from Metahara Sugar Factory and prepared at Metahara Windrow composting field as per the procedures formulated by Mahamuni and Patil [29]. Compositions of filter cake compost, filter cake and vinasse were determined using dried samples which were ground to pass through a 2 mm sieve as described by Pisa and Wuta [40]. Soil pH was determined from a suspension of 1:10 solute: H2O as described by Ndegwa and Thompson [41]. The total OC was estimated by wet combustion procedure as described by Walkly and Black [42]. To determine the total N content of the organic substance wet-oxidation procedure of the Kjeldahl method were employed [43]. Furthermore, total K and P were determined as per procedures prepared by Okalebo *et al.* [44]. The result of analysis is presented in Table 1 below.

Table 1: Selected physicochemical properties of soils of study area prior to field traffic

	Mean	
Parameters	0-30	30-60
Sand (%)	24.69	20.67
Silt (%)	19.64	20.33
Clay (%)	55.67	59.00
Texture	Clay	Clay
Particle density(g/cm^3)	2.47	2.49
Bulk density (g/cm^3)	1.28	1.30
Total porosity (%)	48.00	47.00
Soil pH	8.23	8.30
Soil organic matter (%)	1.11	0.84
Total nitrogen (%)	0.07	0.06
Carbon to nitrogen ratio	8.50	7.80
Available phophorus (ppm)	3.09	3.29

Table 2: Characterization of selected chemical parameters of sugarcane industry residues filter cake, vinasse and filter cake compost

	Organic residues		
Parameters	Filter cake	Vinasse	FC-compost
pH	6.56	4.16	8.00
OC (%)	24.71	13.40	32.71
Nt (%)	1.13	0.69	2.21
Pt (%)	0.42	0.03	1.50
Kt (%)	0.65	1.36	2.62

pH = soil pH, OC = organic carbon; Nt = total nitrogen; Pt = total phosphorus, Kt = total potasium

Agronomic Data Collection: The central two rows of each plot were used for data collection. Number of tillers per m^2 was recorded by counting the number of tillers /per individual shoots in 1 m^2 area at four months from planting date at five random spots within the middle two rows of the plots and average was worked out. Moreover, plant height was measured by taking the average lengths of five randomly taken canes per experimental plot measured from the ground level to the top of the sugarcane at the age of eight months. At harvest (At the age of 22 months), from plot consisting of four furrows twenty millable samples of stalks were randomly taken from the middle two rows to avoid any influence from adjacent plots for measuring stalk weight and juice quality parameters (Polarization, brix, purity and recoverable sugar). The products of millable stalk population count per hectare and mean weight of the millable stalks was used to compute cane yield, while sugar yield was determined following the procedures out lined by Mathur [45].

Data Analysis and Interpretations: Analysis of variance was carried out on soil physicochemical properties and sugar yield to determine the effects of different improvement measures using GLM procedures of the Statistical Analysis System software [46]. For significantly different parameters, the means were separated using Fisher's Least Significant Difference (LSD) test and correlation analyses were also conducted to identify useful associations among key soil and plant variables.

RESULTS AND DISCUSSION

Effects of Subsoiling and Organic Amendments on Selected Soil Physicochemical Properties, Sugar Yield and Yield Components

Effects of Organic Amendments and Subsoiling on Soil Physical Properties

Soil Bulk Density and Total Porosity: Soil bulk density of both top and subsoil layers was significantly ($P < 0.05$) affected by the different improvement measures applied. For both top and subsoil layers, the highest bulk density was recorded in the control plots and the lowest was recorded in the plots where subsoiling was done (Table 3). On the other hand, the highest and lowest total porosity values were recorded in the subsoiled and control plots, respectively. Moreover, the bulk density values recorded in the subsoil were relatively higher than those recorded in the topsoil layer of plots that received the different treatments (Table 3).

The maximum bulk density recorded in the control plots could be due to more compactibility of the soils as compared to those that received organic amendments. The relatively lower bulk density values among the rest of the treatments, on the other hand, might be attributed to the compaction decreasing effect of the sugarcane residues which can be confirmed from the strong correlation ($r = -0.57^{***}$) between the soil organic matter and bulk density (Table 6). The lowest bulk density was recorded in subsoiled plots, which was significantly different from all other treatments, which is attributed to favorable effects of subsoiling by removing compaction effects. Analogues to this, Motavalli *et al*. [47] reported that subsoiling and application of organic amendments reduced bulk density.

The subsoiling operation at a depth of 70 cm with 91 cm shank distance reduced soil bulk density by 19.70% and 21.94% below the control for both top and subsoil layers, respectively. This observation is in close agreement with the results obtained by Reichert *et al*. [48] who reported the highest decrease in bulk density due to subsoiling. The soil total porosity was also significantly ($P < 0.05$) affected by the different treatments applied for both layers. The maximum porosity (57, 51%)

Table 3: Effects of organic amendments of different doses and subsoiling on selected soil physical properties

	Parameters					
IM	ρbt (g cm^{-3})	ρbs (g cm^{-3})	ft (%)	fs (%)	PRt (MPa)	PRs (Mpa)
Control	1.32^{a}	1.55^{a}	46.00^{d}	38.00^{c}	2.41^{a}	2.03^{a}
FC-1	1.28^{abc}	1.34^{b}	48.00^{bcd}	46.00^{b}	2.08^{b}	1.67^{abc}
FC-2	1.18^{cb}	1.38^{b}	52.00^{bc}	45.00^{b}	1.94^{bc}	1.41^{cd}
FC-3	1.27^{ab}	1.41^{b}	48.00^{bcd}	43.00^{b}	1.98^{bc}	1.83^{ab}
V-1	1.29^{ab}	1.40^{b}	48.00^{bcd}	44.00^{b}	2.09^{ab}	1.92^{ab}
V-2	1.20^{abc}	1.38^{b}	51.00^{bcd}	44.00^{b}	2.14^{ab}	2.01^{ab}
V-3	1.17^{bcd}	1.37^{b}	52.00^{abc}	44.00^{b}	1.95^{bc}	1.51^{bcd}
COM-1	1.17^{bcd}	1.36^{b}	53.00^{abc}	45.00^{b}	2.13^{ab}	1.84^{ab}
COM-2	1.16^{cd}	1.32^{b}	53.00^{abc}	45.00^{b}	1.90^{bc}	1.20^{c}
COM-3	1.26^{abc}	1.41^{b}	49.00^{bcd}	47.00^{b}	2.18^{ab}	1.21^{c}
Subsoiling	1.06^{d}	1.21^{c}	57.00^{a}	51.00^{a}	1.67^{c}	1.16^{d}
LSD (%)	0.13	0.108	0.051	0.044	0.325	0.407

$FC_{1,2,3}$ = filter cake doses, $V_{1,2,3}$ = vinasse doses, $com_{1,2,3}$ = compost doses and LSD = least significant difference, IM= improvement measures, ρbt = topsoil bulk density, ρbs = subsoil bulk density, ft = topsoil total porosity, fs = subsoil total porosity, PRt = top soil penetration resistance, PRs = subsoil penetration resistance

was recorded for subsoiled plots respectively for top and subsoil layers, which could be due to the application of subsoiling that lowered the soil bulk density. However, the lowest porosity was recorded in the plots that were compacted and without residues. The lowest porosity for control plots could be attributed to decreased pore spaces due to soil compaction.

Subsoiling increased the total porosity of the top and subsoil layers by 23.91 and 34.21%, respectively, over the control. Therefore, it could be concluded that subsoiling operation can be used when there is a problem related to compaction and severe plough pan or any hard pan within the underlying soil layers, which causes restricted root growth. To reduce compactibility of soils during sugarcane field cultivation, compost is the best improvement measure. This can be attributed to the improvement in total porosity of soil, which can be evidenced by positive correlation ($r = 0.56^{***}$) between total porosity and soil organic carbon (Table 6).

From among the filter cake rates, FC-2 gave better result in that it decreased the bulk density of top and subsoil, respectively, by 10.61 and 10.97%, increased the total porosity by 13.04 and 18.42%. Similarly, from among the vinasse rates, V-3 gave relatively better results in which case it reduced the bulk density by 11.36 and 11.61%, increased total porosity by 13.04 and 15.79%, respectively, for top and subsoil layers. The COM-2 decreased the bulk density, respectively, for top and subsoil layers by 12.12 and 14.84% and improved total porosity by 15.22 and 18.42%. As compared to all the three residues, the subsoiling was the best in improving all the soil conditions listed above (Table 5). While, the maximum decrease in bulk density was achieved by 22.07 t ha^{-1} of compost next to subsoiling treatment. Moreover, 105 $m^3.ha^{-1}$, 30 and 22.07 t ha^{-1} doses, respectively for vinasse, filter cake and filter cake compost doses were the best doses of organic amendments in reducing compaction effects (Table 3).

Soil Penetration Resistance: The penetration resistance also revealed significant ($P < 0.05$) response to various improvement measures (Table 3). Maximum penetration resistance was found in the control treatment for both top and subsoil layers. On the other hand, the lowest penetration resistance values were recorded in the treatment which received subsoiling, followed by that in FC-2 for top layer and COM-2 for subsoil treatments. The lowest soil penetrometer readings for subsoiling treatment could be attributed to the loosening effect of this operation. Moreover, reduced penetration resistance as a result of compost use is commonly reported. The decrease in penetration resistance in filter cake and compost incorporated plot may also be a reflection of improved soil structure and diluting effect of filter cake and compost of the soil. Reduced penetration resistance due to compost application was also reported by Edwards *et al*. [49].

According to the finding reported by Aase *et al.* [50] the ability of sugarcane plant roots to penetrate soil has been shown to be restricted as the pressure exceeds 2 MPa and finally ceases at 3 MPa. As per these critical limits, most of the improvement measures resulted in significant reduction in compaction compared to the control. The different rates of the amendments resulted in different rates of change or improvement in soil properties. From among the filter cake doses, FC-2 decreased the penetration resistance by 21.16 and 30.54%, respectively, for the top and subsoil layers. Similarly, from among the vinasse rates, V-3 gave relatively better results in which case it reduced the penetration resistance of the top soil by 13.28% but decreased that of the subsoil by 4.30%. The COM-2 decreased penetration resistance by 19.50 and 40.90%, respectively, for top and subsoil layers. Comparing the three residues, it can be seen that filter cake and its compost form are more effective in reducing penetration resistance, through probably their favorable effect on moisture retention and dilution effect. As compared to all the three residues, the subsoiling was superior in reducing penetration resistance. Accordingly, it reduced the penetration resistance by 30.71 and 42.86%, respectively, for the top and subsoil layers. Similarly, Raper *et al.* [51] reported that subsoiling of a severely compacted soil layer reduced its penetration resistance significantly (Table 3).

As noted by Henriksen *et al*. [52] subsoiling is only a way to loosen up a compacted soil and do not serve as a protection. But it is important to recognize that using subsoiling is only a short-term solution to soil compaction and is very expensive. If compactions by machines are prevented by controlled wheel traffic the effects of subsoiling could last for three years [53]. Therefore, ultimately in the long term, agronomic practices such as avoiding all operations when the soil moisture content is high and the use of filter cake, vinasse and their compost must be adopted to minimize wheel traffic. Incorporation of appropriate doses and types of organic amendments can give better and sustainable results against soil compaction by reducing bulk density and penetration resistance values and improving the salient soil properties, such as soil structure compaction [54].

Botta *et al.* [55] also pointed out that ploughing after subsoiling can aggravate soil compaction. On the other hand [56] reported that subsoiling the soil to greater depths than necessary requires additional tillage energy, promotes future deeper compaction and continuous subsoiling of the same field may reduce yields. It is therefore necessary to identify appropriate subsoiling depth in order to benefit better from subsoiling. Finally, it can be recommended that to reduce penetration resistance of compacted soils, depth targeted and site specific subsoiling operation can be done after ploughing to protect severe compaction of tractor traffic.

Response of Soil Chemical Parameters to Different Rates of Sugarcane Residues and Subsoiling

Soil pH: No significant improvement in soil pH was achieved due to the different improvement measures tested (Tables 4). The pH after application of the three residues and subsoiling remained above 8, which falls within the range of strongly alkaline as per pH rating suggested by Tekalign Tadese [57]. Nevertheless, different degrees of decrease in pH due to the application of the different rates of residues were noted. Accordingly, a decrease in pH by 4.39% (Topsoil) and 4.72% (Subsoil) due to application of vinasse at the rate of 105 m^3 ha^{-1} were recorded. The other treatments resulted in very low levels of decrease in soil pH.

The relatively low decrease in pH as a result of the different improvement measures, particularly of the residues, could be attributed to the expected high buffering capacity of the soil coming from its high clay content. Furthermore, the better decrease in soil pH due to the application of vinasse could be ascribed to its acidity as was noted from its low pH value (Table 2). The soil acidification effects of vinasse were also reported in other studies [58]. In line with the findings in this study, Pradeep [59] reported that application of filter cake and vinasse decreased soil pH.

Soil Organic Carbon and Total Nitrogen: Application of different rates of residues from the sugar industry resulted in significant improvement of the topsoil organic carbon content as compared to the control (Tables 4). Nevertheless, the difference in soil organic carbon content of the subsoil layer as a result of application of different rates and types of residues was not significant ($P = 0.05$). The improvements in organic carbon content ranged from 9.73% due to subsoiling to 14.05% due to the application of filter cake compost at the rate of 22.07 t ha^{-1}. However, the increase in organic carbon content was not commensurate with the increase in the rate of application of the respective residues.

The significant increase in topsoil layer soil organic carbon content of the soil following application of filter cake, vinasse and filter cake compost with respect to control might be attributed to the high content of organic carbon in these residues (Table 4). Similarly, the increase in organic carbon content following subsoiling could be associated with production of more root biomass following the improvements and downward movement from the surface. In consent with the findings of this study, Datta *et al*. [60] also reported increase in organic carbon content following application of filter cake and vinasse to soils. Furthermore, after making extensive review of research done on vinasse, Newey [61] pointed out that vinasse contains high organic carbon in it. The positive influences of the added residues on soil bulk

Table 4: Effects of organic amendments of different doses and subsoiling on selected soil chemical properties

	Parameters				
IM	pHt	pHs	Oct (%)	Nt (%)	Pt (ppm)
Control	8.43	8.47	1.85[d]	0.05[d]	3.02[b]
FC-1	8.13	8.15	1.98[cb]	0.095[ab]	4.00[ab]
FC-2	8.17	8.29	2.04[ab]	0.067[bcd]	4.49[ab]
FC-3	8.24	8.19	1.99[b]	0.067[bcd]	3.48[b]
V-1	8.20	8.33	1.89[cd]	0.053[d]	3.37[b]
V-2	8.33	8.31	1.95[bc]	0.057[cd]	4.63[ab]
V-3	8.06	8.07	2.00[b]	0.067[bcd]	3.31[b]
COM-1	8.33	8.41	2.00[b]	0.067[bcd]	3.99[ab]
COM-2	8.33	8.36	2.11[a]	0.097[a]	5.83[a]
COM-3	8.30	8.32	2.00[b]	0.083[abc]	4.33[ab]
Subsoiling	8.38	8.42	2.03[ab]	0.051[d]	3.08[b]
LSD	ns	ns	0.09	0.03	0.84

$FC_{1,2,3}$ = filter cake doses, $V_{1,2,3}$ = vinasse doses, $com_{1,2,3}$ = compost doses and LSD = least significant difference, IM= improvement measures; pHt = topsoil pH, pHs = topsoil pH, SOCt = topsoil organic carbon; Nt = topsoil total nitrogen; Pt = topsoil available P

density, total porosity and penetration resistance could, therefore, be the results of increased soil organic matter content. The increase in soil organic matter content, through its favorable impacts on biological activity, nutrient supply, soil structure and water retention, can help to keep compaction at a level that is not detrimental to the growth of sugarcane roots.

Consistent with increases in soil organic carbon content, most of the improvement measures tested significantly ($P < 0.05$) improved the total nitrogen status of the soil over the control (Tables 4). The improvements in total nitrogen content of the topsoil ranged from 2% due to subsoiling to 94% due to application of filter cake compost at the rate of 22.07 t ha^{-1}. By and large, filter cake and its compost were slightly better in improving the total nitrogen content of the soil as compared to the vinasse (Table 4). The relatively lower improvement associated with vinasse might be associated with the large quantity of water in the vinasse, which may subject the nitrogen present to losses by volatilization and also leaching. The overall improvements in total nitrogen due to the application of the three residues could be associated with the increase in organic matter as well as their high content of nitrogen. This result is in agreement with the finding by Muchovej and Newman [62] who reported high total nitrogen from sugarcane residues due to high concentration of nitrogen in the substances.

Soil Available P: Similar to the other soil properties, the tested improvement measures affected the available top soil layer P of the soil significantly ($P < 0.05$) (Tables 4). Accordingly, the highest available topsoil layer P was recorded in soils that received filter cake compost at the rate of 22.07 t ha^{-1}, while the lowest was recorded in soils of the control plot. The improvements due to the application of the different improvement measures ranged from 1.99% in subsoiled plot soil to 93.05% in the soil where filter cake compost was applied at the rate of 22.07 t ha^{-1}. Although the improvement in available P as a result of application of different rates of the residues is significant, as per the rating by Landon [63] the available P remained still in the low range except in the soil where 22.07 t ha^{-1} of filter cake compost was applied in which case it became medium. This indicates that rate of mineralization of P present in these residues is not fast enough to meet the P requirement of the crop and, hence, integrated application of inorganic and organic P sources is required. In agreement with the findings in this study, Sarwar *et al*. [64] also observed increase in available phosphorus in soils treated with vinasse and filter cake, respectively.

Effects of Organic Amendments and Subsoiling on Sugarcane Yield and Yield Components

Tiller Counts: Application of different types of improvement measures affected tiller counts significantly ($P < 0.05$). The maximum tillers (664) were recorded for subsoiling followed by filter cake compost (640) which decreased to the minimum (452) in control. The maximum tillers recorded for subsoiling and filter cake compost could be attributed to accelerated process of tiller development as a result of improved soil conditions and fertility status compared to the control plot for which minimum tillers were recorded. The improved soil condition which is directly related to improved soil organic carbon can be confirmed by positive correlation ($r = 0.36^*$) between tiller counts and soil organic carbon. The minimum tillers determined for control plot also could be due to the impeded ability of roots in extracting soil nutrients as a result of soil compaction. This result is in line with Li *et al*. [65] who reported more tiller when compacted soil was loosened.

Height of Sugarcane: Plant height was significantly ($P < 0.05$) affected by improvement measures applied to the compacted soil. The maximum cane height was exhibited in subsoiling plot (2.01 m) followed by compost plot (1.93 m) which decreased to the minimum (1.58 m) for the control plot. The maximum cane height recorded for subsoiling could be due to removal of the compaction effect. Similarly, Nidal [66] reported that

Table 5: Effects of organic amendments of different doses and subsoiling on sugar yield and yield components

	Parameters		
IM	TC	H (m)	Sugar yield (tone)
Control	452.00^{c}	1.58^{f}	15.74^{d}
FC-1	589.00^{ab}	1.88^{bc}	17.32^{c}
FC-2	611.00^{ab}	1.91^{b}	17.87^{bc}
FC-3	570.00^{ab}	1.89^{bc}	17.55^{c}
V-1	484.00^{bc}	1.61^{f}	15.89^{d}
V-2	562.00^{abc}	1.71^{e}	15.94^{d}
V-3	590.00^{ab}	1.73^{de}	17.38^{c}
COM-1	560.00^{abc}	1.79^{d}	17.99^{abc}
COM-2	640.00^{ab}	1.93^{b}	18.75^{ab}
COM-3	580.00^{ab}	1.81^{cd}	17.09^{c}
Subsoiling	664.00^{a}	2.01^{a}	18.95^{a}
LSD	111.06	0.08	1.01

TC = tiller count, H = height, IM = improvement measures

Table 6: Pearson correlation analysis of some soil physicochemical parameters and sugar yield

	ρb	f	PR	SOC	N	P	TC	H	Yield
ρb	1	-0.99***	0.31^{ns}	-0.57***	-0.22^{ns}	-0.03^{ns}	-0.09^{ns}	-0.46**	-0.55***
f		1	-0.31^{ns}	0.56***	0.22^{ns}	0.03^{ns}	0.09^{ns}	0.45**	0.54***
PR			1	-0.32^{ns}	-0.15^{ns}	-0.01^{ns}	-0.12^{ns}	-0.44*	-0.51**
SOC				1	0.16^{ns}	0.07^{ns}	0.36*	0.50**	0.69***
N					1	0.3^{ns}	0.14^{ns}	0.17^{ns}	0.16^{ns}
P						1	0.15^{ns}	0.0.1^{ns}	0.02^{ns}
TC							1	0.36*	0.06^{ns}
H								1	0.49**
Yield									1

ρb = soil bulk density, f = soil total porosity, PR = soil penetration resistance, SOC = soil organic carbon, N = soil total nitrogen, P = soil available phosphorus, TC = tiller count, H == height ***, ** and * = Significant at P < 0.001, p< 0.01 and P < 0.05, respectively; ns = Not significant.

subsoiling removed the compaction effects and improved soil properties and plant growth. The maximum height exhibited by composted filter cake could be due to the reduced bulk density and increased total porosity of soil which consequently results in better soil conditions for roots and uptake of soil nutrients as compared to the control plot. This can be evidenced by negative correlation (r = -0.46**) between height and bulk density. This is in agreement with Bengough *et al*. [67] who reported that plant height decreased with increase in bulk density.

Sugar Yield: Owing to improvements in soil physical, chemical and possibly biological conditions of the soil as a result of the different improvement measures, significantly (P < 0.05) increase in sugar yield was recorded on most plots (Tables 4). The highest sugar yield was recorded in the subsoiled plots followed by the plots that received 22.07 t ha^{-1} of filter cake compost, while the lowest sugar yield was recorded in the control plot. Almost all the improvement measures improved the sugar yield as compared to the control. Accordingly, the increase in sugar yield ranged from 0.95% due to application of vinasse at the rate of 35 m^3 ha^{-1} to 20.39% from subsoiling plot. The fact that the subsoiling resulted in more increment in yield than those plots that received residues indicates that the impacts of subsoiling are more immediate than the application of residues. Among the three residues, application of filter cake compost at the rate of 22.07 t ha^{-1} seems better in improving sugar yield due to probably its positive effects on bulk density, porosity, penetration resistance and nutrient supply. Moreover, the better yield recorded by filter cake compost may also be associated to the better organic carbon of this residue. This can be confirmed by strong positive correlation (r = 0.69 ***) between yield and soil organic carbon.

Similar to the findings of this study, various researchers reported the positive effects of the tested improvement measures on sugar yield. As mentioned by Usaborisut and Niyamapa [68] subsoiling improved sugar yield through removal of compaction. Gomez and Rodriguez [69] also reported increment in sugar yield over the control due to incorporation of vinasse and filter cake, respectively. Pankhurst *et al*. [70], Tesfaye *et al*. [71] also reported that application of improvement measures such as subsoiling and residues as source of organic matter, reduced soil compaction by decreasing the values of bulk density and increasing porosity.

CONCLUSION AND RECOMMENDATION

The results of the study revealed that all the organic amendments and subsoiling were effective in improving the investigated soil physicochemical properties such as soil bulk density, total porosity and penetration resistance of top and subsoil layers, soil total nitrogen of top layer and available soil phosphorus and soil organic carbon of top layer and sugarcane yield. Soil compactibility caused by heavy machinery during sugarcane production can be reduced by incorporating sugarcane residues before machine passes. Moreover, once compaction has occurred, soil depth targeted and site specific subsoiling operation can be used to resolve any problem related to compaction and severe plough pan within the underlying soil layers, which causes restricted root growth. This study is limited to light soil management and few doses of the residues. Higher or lower than the current rates could give better results on different soil types. Therefore, additional studies are needed with different dose of the residues on soil management unit groups of the other estate soils and Metahara heavy soil management unit group.

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