Anaerobic degradation of municipal organic waste among others composting techniques improves N cycling through waste-soil-plant continuum

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Abstract

This study aimed to examine the effect of composting techniques of municipal organic solid waste (MSW) for (i) total carbon (C), nitrogen (N) losses, and changes in its chemical characteristics during composting phase and (ii) value of the composted materials as fertilizer when applied to vegetables. Treatments included: aerobic composting (AC), anaerobic composting (ANC), co-composting (CC) and open dumping (OD) for 4 months. During the composting phase, about 61, 50, 35, and 13% of the initial N was lost from CC, AC, OD, and ANC, respectively. The respective values in case of total C loss were 17, 13, 14 and 11%. After field application, about 41% of the applied organic N was mineralized from ANC material, whereas the respective values for OD, CC and AC were 25-26, 15-16, and 12-19%. Consequently, dry matter (DM) yield and vegetable N uptake from the resultant compost were in the order ANC>OD>CC>AC. Moreover, vegetable apparent N recovery (ANR_i) was the highest from ANC (spinach: 36 and carrot: 45%) followed by OD (26 and 34%), CC (18 and 26%) and AC (18 and 24%) material. When composting N losses were taken into account during calculations, about 31-39, 17-22, 9-10, and 7-12% of the N collected from filth depots ended up in plants from ANC, OD, CC and AC, respectively. We concluded that ANC results in least C and N losses during the composting phase and greatest N mineralization in the soil, which enhances vegetable yield, N recovery and thereby the N cycling through waste-soil-plant continuum.

Keywords: Nitrogen cycling, composting, organic farming, kitchen gardening, solid waste management, nutrient management

1. Introduction

Rapid urbanization, improved living standards, and changing habits for utilization of food by the people of Pakistan have increased the amount of municipal solid waste (MSW) production. According to an estimate, about 28 million tons of MSW is being produced annually in Pakistan, i.e., at a rate of 0.4 kg capita⁻¹day⁻¹. About 60% of the total produced waste in the country is organic or biodegradable (Kamran *et al.*, 2015). This huge amount of waste is being dumped in open landfills along roadsides, railway lines, in empty plots and streets by municipalities or local waste producer. This practice provides habitat for disease causing vectors (Achudume and Olawale, 2007) and contributes to air, water and soil pollutions (Giusti, 2009; Yazdani *et al.*, 2015).

To minimize the above mentioned problems, it is believed that the solid waste management must be given special consideration during urban development and planning, especially in developing countries like Pakistan. Attempts have been and are being made for this purpose. These include (i) landfilling of the MSW where the waste is safely disposed-off in the lined pits and sealed in the pits thereafter and (ii) combustion of the waste in an incinerator. However, both these methods are very costly, require skillful labor, provide temporary solutions and result in secondary pollution, such as production of toxic gases, ash, and leachate (Giusti, 2009). In Pakistan, municipal waste management through landfilling and incineration is expensive and would not be practically feasible solution for all areas, especially in southern Punjab. Since people of this region are mainly dependent on agriculture for their livelihood, therefore, municipal solid waste composition is highly organic in nature. For such waste, optimized biological processes or means for waste reduction, reuse and recovery would be preferable. These processes convert the green waste or

food leftover in to organic fertilizers such as compost (Favoino and Hogg, 2008; Hargreaves *et al.*, 2008b; Boldrin *et al.*, 2009 Kumar, 2011) that may fulfill the increasing demand of chemical fertilizers for crop production in Pakistan, which is about 13% annually (Pakistan Bureau of Statistics, 2016).

Moreover, it is also believed that recycling as an organic fertilizer can be a promising option for healthy environment and sustainable agriculture. Therefore, fertilizer value of the composted waste has been extensively studied but main focus had been on livestock wastes (Scotti *et al.*, 2015; Rigby *et al.*, 2016; Shah *et al.*, 2012, 2013, 2016a,b; Moreno *et al.*, 2017), whereas little work has been done on fertilizer value of MSW compost (Hargreaves *et al.*, 2008b; Romero *et al.*, 2013). Likewise, to the best of our knowledge no work has been done so far investigating the effect of various composting methods on N cycling from waste-soil-plant continuum.

Composting techniques differ in terms of controlling the environmental condition during the waste degradation such as aerobic or anaerobic, which influences the quality of end-product and thereby can affect on-farm N cycling (Shah *et al.*, 2016a,b). These differences in storage conditions might affect N losses through ammonia, nitrous oxide emissions and leaching. Sagoo *et al.* (2007) found that anaerobic condition through compaction and covering of broiler litter heaps can reduce total N losses by 70% and ammonia emission by 90% as compared to conventional stockpiling. Shah *et al.* (2016a) reported that N losses can be restricted by about 72% through covering the heaps with an impermeable plastic sheet. Moreover, the storage conditions not only affect the level of N losses but also determine the characteristics of the end-product which can be decisive for subsequent decomposition and N mineralization processes. Anaerobic storage of waste

results in end product with greater N content in the form of mineral-N (Shah *et al.*, 2012, 2016a,b). Moreover, during the anaerobic degradation process easily degradable organic compounds, such as volatile fatty acids, are produced. Consequently, microbial degradation and N mineralization rates are high in case of anaerobically decomposed materials in comparison to aerobically decomposed materials (Shah *et al.*, 2012, 2016a,b). In case of aerobic decomposition, stable N compounds are formed due to breakdown of easily degradable N compounds earlier during composting phase, which results in relatively lower decomposition and mineralization when applied to soil as a fertilizer (Shah *et al.*, 2016a,b). Aerobic-compost application have been found to be positively affecting the total N content in soil (Civeira 2010). It have been reported that between 5 and 60% of the N applied with aerobic-compost is mineralized during the year of application, depending on its characteristics (Martínez-Blanco *et al.*, 2013). However, to the best of our knowledge no sound data set exist regarding the effects of anaerobically composted and/or co-composted MSW on changes in MSW characteristics and its downstream impacts on fertilizer value of N. Therefore, this study aimed to (i) determine the effect of composting methods (anaerobic, aerobic, co-composting and open dumping) on dry matter (DM), C and N losses during composting, and changes in its chemical characteristics, and (ii) estimate fertilizer value and vegetable yield after compost application to soil.

2. Materials and Methods

Study was carried out at COMSATS Institute of Information Technology (CIIT), Vehari (latitude 30.0318° N and longitude 72.3145°E) during 2015-2016. The study consisted of two experiments: 1) composting and 2) compost application in the pots containing soil where carrot and spinach were grown.

2.1. Composting experiment

Municipal solid waste (MSW), about 1 week older was collected from the containers that were installed by Tehsil Municipal Administration at various locations within the Vehari city. After collection, the waste was manually segregated to obtain the organic fraction (i.e. kitchen waste, tree trimmings, grass leaves and stem, fruit and vegetable residues and animal wastes). Thereafter, the selected waste was chopped with a chopping machine into fine homogenized material with particle size of up to 4 cm. Immediately, thereafter portions of 120 kg of the homogenized waste were put on a clean concrete floor to make conical heaps with a height of about 1 m and a base diameter of about 1.5-2 m. We used four composting techniques (each represent a treatment) that include (i) Aerobic composting (AC): biological decomposition with aeration through frequent turnings in open air, (ii) Anaerobic composting (ANC): biological decomposition without aeration in controlled conditions, (iii) Co-composting (CC): aerobic degradation of MSW with farmyard manure, and (iv) Open dumping (OD): stockpiling of waste in the open air. All these treatments were arranged in a randomized complete block design (RCBD) with three replicates. Each AC heap was turned once in two weeks manually using pitchfork to facilitate aerobic degradation. For ANC, a pit of 1 m × 1 m × 1 m was made and an impermeable plastic sheet (0.15 mm thick polyethylene sheet) was used with lining at its bottom and at the top to make it airtight completely. Waste was packed in this sheet and pit was closed by a layer of soil in order to ensure anaerobic conditions. The CC was done by mixing MSW with the farmyard manure at a ratio of 2:1. These heaps were kept for 120 days i.e., from the first week of June till the first week of October, 2015. During experimental periods, all the aboveground heaps were regularly watered to maintain the moisture content of the waste at about 60%

using a low-cost moisture meter (SM-150, Delta-T Service, UK). On the last day of the storage phase, waste from the heaps was collected and weighed individually. Both at the start and at the end of the composting period, one composite sample (1 kg fresh wt.) was collected from each heap. The composite sample consisted of 20-30 sub-samples taken randomly from various locations of a heap. These samples were oven-dried at 105 °C for 24 hours and analyzed for pH, electrical conductivity (EC), dry matter (DM), organic matter (OM), total organic carbon (TOC), oxidizable organic carbon (OOC), fixed solids (FS), total N and mineral N contents.

Determination of EC and pH in waste and soil samples were done from 1:10 extracts (sample/ 0.01M CaCl₂) using calibrated EC meter (Lovibond Senso Direct

Con110) and pH meter (EZDO 6011), respectively. The OM of waste samples was determined by loss on ignition method. The TOC, and OOC was thereafter calculated (Estefan *et al.*, 2013) and from the loss on ignition method, remaining solids were termed as fixed solids (FS). Total N content of the waste, plant and soil samples were determined by Kjeldahl method as described by Estefan *et al.* (2013). Mineral N content of soil, and compost samples was determined by distilling their extracts using boric acid as receiver, following titration with 0.01N H₂SO₄ solution (Estefan *et al.*, 2013). Total DM, C and N losses during the storage period were estimated through the mass balance method by comparing their contents just before and after the storage phase (Shah *et al.*, 2016a,b).

Table 1. Mean values (n=3) of physio-chemical characteristics of soil (sandy loam) used in the experiment.

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Characteristics	Unit	Values
Electrical Conductivity (1:10)	dSm ⁻¹	0.25± 0.11
pH-H ₂ O extract (1:10)	-	8.2± 1.20
Organic Matter	%	0.4 ± 0.01
Available Phosphorous	ppm	5.7 ± 0.90
Available Potassium	ppm	7.4± 10.25
Saturation percentage	%	39.3 ± 3.61
Total Nitrogen	mg kg ⁻¹	400 ± 1.00
Mineral Nitrogen	mg kg ⁻¹	7.6±0.14

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2.2. Pot experiment

Soil taken from an agriculture field (Table 1) of CIIT, Vehari was properly mixed and homogenized after passing through a 4 mm sieve to remove plant roots and other debris. Thereafter, earthen pots (surface area 0.035 m²) was filled with 7 kg soil in each pot. Subsequently, all the four compost materials (AC, ANC, CC and OD material) were manually incorporated, in the

top 15 cm to avoid ammonia emission (Webb *et al.*, 2010), at an application rate of 20 kg N acre⁻¹ for carrot and 40 kg N acre⁻¹ for spinach as per recommendation of local Agriculture department. In addition, a control was included with similar soil preparation, but without the addition of compost. All these treatments were arranged in a randomized complete block design with four replicates.

Two days after treatment application, five seeds of carrot and spinach were sown in their respective pots. After germination, only three seedlings (healthy, uniform and at proper distance from each other) for carrot and spinach were maintained in each pot. During the growing period, soil moisture content in the pots was maintained at ca. 60 % water holding capacity (WHC) throughout the experimental period in order to avoid denitrification losses. To achieve this, water was applied daily using a hand sprinkler with extreme care whilst following the increase in WHC with a moisture meter (SM-150, Delta-T Service, UK).

2.3. Plant Harvesting

During the experimental period, spinach was harvested three times: 30, 61 and 90 days after sowing. At 1st and 2nd cut, plants were clipped 2 cm above the soil surface with a scissor, whereas in case of 3rd cut plants were clipped at the ground level. Thereafter, roots were collected and separated from soil in each pot in order to estimate root DM yield and N uptake. For this purpose, the whole soil clump from a pot was taken out and placed in a container filled with cold water. After 2 h of soaking, the clump was manually divided into 6–8 pieces. These were taken out of the container one by one and placed on a 0.5 mm mesh frame to separate roots from soil with a jet of tap water. In addition, the remaining roots were recovered by decanting the soil-water mixture through a sieve with the same mesh size.

Carrots were harvested after 85 days of sowing. During harvest, whole carrot plant was uprooted by a gentle pull together with loosening of soil. Thereafter, roots were separated from shoots, and separately washed with distilled water, blotted dry using tissue paper. Fresh weight (g) of roots and shoots was recorded. Thereafter, representative root and shoot samples were oven-dried at 70 °C for 48 hours, ground to pass

a 1 mm sieve and analyzed for total N content using Kjeldahal apparatus. At the end of the experiment, soil samples from each pot were taken from top to bottom using an augur, air-dried and analyzed for mineral N (ammonium-N + nitrate-N) content according to the procedure as described by Shah *et al.* (2013).

2.4. N mineralization and plant N recovery calculations

Final mineral N in the soil with the total apparent plant N uptake (shoots + roots) from applied compost enabled us to create an N balance as presented in Table 4 in order to estimate the amount of net organic N mineralized from the applied compost materials as described by Shah *et al.* (2013). Moreover, total N recovery as a fraction of (i) field applied N with composts (TNR_f) and (ii) collected N from the filth depots for each harvest (TNR_c) was calculated (Shah *et al.*, 2012; Shah *et al.*, 2013; Shah *et al.*, 2016a,b) as:

$$\text{TNR}_f (\%) = \frac{(\text{TNU}_{\text{treatment}} - \text{TNU}_{\text{control}})}{\text{TN}_{\text{applied}}} \times 100 \quad \text{Eq. (1)}$$

Where, TNU_{treatment} and TNU_{control} is the total N uptake by plants in compost applied and controlled pots (g m⁻²) respectively. TN_{applied} represents total applied N in pots in compost (g m⁻²). Thereafter, total N recovery as a fraction of collected N from the filth depots (TNR_c) was calculated (Shah *et al.*, 2012; Shah *et al.*, 2016a,b) as

$$\text{TNR}_c (\%) = \frac{(\text{TN}_w - \text{TN}_{\text{loss}_{\text{storage}}}) \times \text{TNR}_f}{\text{TN}_w} \times 100 \quad \text{Eq. (2)}$$

Where, TN_w is the total N initially in MSW as taken from filth depot, TN_{loss_{storage}} is the N lost during composting and TNR_f is the fraction of N recovered during field experiment

2.5. Statistical analysis

The chemical characteristics of composts, N uptake by plants, N mineralization and N recovery values during experiment were analyzed using analysis of variance in STATISTIX 8.1. When, the overall main effects, were statistical significant, treatments were further compared using least significant difference (LSD) test at 5% probability level.

3. Results

3.1. DM, C and N losses during composting phase

Total DM, C and N losses during composting of MSW are presented in Figure 1. Mass balances of the heaps

Figure 1. Dry matter (DM), carbon (C), and nitrogen (N) losses from MSW subjected to various composting techniques. Error bars represent standard error ($\pm$) of the mean. Data bars with same texture but carrying different letters are significantly different from each other.

3.2. Changes in chemical characteristics of MSW during composting

Chemical characteristics of MSW before and after composting period are shown in Table 2. At the end of composting period, a decrease in pH in ANC (8.07 vs. 7.43) and CC material (8.07 vs. 8.03) was recorded, whereas it increased in case of AC (8.07 vs. 8.23) and OD (8.23 vs. 8.24) material as compared to MSW be-

revealed that the highest total DM losses occurred in the CC waste heaps and the lowest in case of OD heaps. On average, 47% of the initial DM from CC, 24% from the AC, 7% from the ANC and 6% from the OD heaps were lost during 120 days of experimental period. Total C losses were 17, 13, 11 and 14%, from CC, AC, ANC and OD, respectively. Highest total N losses occurred in the CC waste heaps and the lowest in ANC heaps. Interestingly, five-folds higher N losses were found from the former as compared to the latter treatments, i.e., 61 vs. 12% of the initial total N.

These fractional N losses in case of AC and OD were 50 and 35% of the total initial N, respectively.

fore composting (Table 2). Variations in the EC from initial to final stage of composting were quite significant. In case of OD, there was a decrease in EC from 4.86 to 3.55 dS m^{-1} while it remained almost the same in case of AC (4.80 dS m^{-1}). However, in case of CC and ANC, value was higher than initial EC of fresh MSW, i.e., 5.97 and 6.08 dS m^{-1} , respectively. The OM, OOC and TOC was significantly lost from fresh MSW during all composting techniques and fixed

solids (FS) were increased in all composts. Among the compost treatments, OM content was the highest in ANC (42%) and least in case of CC (31%). Similarly OOC and TOC were the highest in the former treatment (18 and 24%, respectively). Interestingly, with

respect to fresh MSW before composting inorganic N content had increased by about 20% in ANC material (2.18 vs. 1.81 g kg⁻¹ DM), whereas it had decreased by 25 (1.36 vs. 1.81), 25 (1.35 vs. 1.81) and 30% (1.28 vs. 1.81) in OD, CC and AC treatments, respectively (Table 2).

Table 2. Chemical characteristics of MSW subjected to various composting techniques. Values followed by (±) within a column represent the standard error found.

Treatment	pH	EC† (dS m ⁻¹)	N‡ (g kg ⁻¹)	Mineral N (g kg ⁻¹)	OM! (%)	OOC‡ (%)	TOC‡ (%)	C:N	Fixed solids (%)
Before composting									
Fresh MSW	8.07 (±0.03)	4.86 (±0.94)	14.1 (±0.28)	1.81 (±0.09)	60.31 (±2.83)	26.23 (±1.23)	34.98 (±1.64)	24.813 (±1.31)	39.69 (±2.83)
After composting									
OD	8.24 (±0.12)	3.55 (±0.21)	9.7 (±0.19)	1.35 (±0.02)	36.24 (±3.26)	15.75 (±1.42)	21.02 (±1.89)	21.670 (±1.52)	63.76 (±3.26)
AC	8.23 (±0.12)	4.80 (±0.26)	9.2 (±0.30)	1.28 (±0.03)	37.83 (±3.26)	16.45 (±1.42)	21.94 (±1.89)	23.850 (±1.52)	62.17 (±3.26)
CC	8.03 (±0.09)	5.97 (±0.79)	10.2 (±0.15)	1.36 (±0.08)	31.21 (±3.26)	13.57 (±1.42)	18.10 (±1.89)	17.750 (±1.52)	68.79 (±3.26)
ANC	7.43 (±0.20)	6.08 (±0.38)	13.2 (±0.24)	2.18 (±0.03)	41.85 (±3.26)	18.20 (±1.42)	24.28 (±1.89)	18.397 (±1.52)	58.14 (±3.26)

*Not determined, †Electrical conductivity, ‡Nitrogen, !Organic matter, ‡Oxidizeable organic carbon, ‡Total organic carbon

3.3. Assessment of fertilizer value

3.3.1. DM yield and N uptake of vegetables

The observed DM yield and N uptake of carrot and spinach after application of compost materials are presented in Table 3. Application of compost materials significantly ($P<0.05$) increased the DM yield of both spinach and carrot as compared to the unfertilized control. Among the compost treatments, total DM yield was the highest from ANC and lowest in AC and/or CC both for spinach and carrots. On an average, DM yield pattern observed in both vegetables was in the order: ANC>OD>CC>AC. Of the total DM, the greater fraction came from the roots for carrots and shoots in case of spinach. In case of spinach, contribution of 1st cut

was the greatest as compared to the latter cuts (data not presented). Similar to DM yield, application of compost material to both vegetables significantly increased total plant N uptake as compared to unfertilized control. Among the compost treatments, the greatest N uptake by spinach and carrot was observed from ANC treatments and the least for AC and/or CC (Table 3). The total N uptake from the former treatment (ANC) was 46% higher in carrot and around 40% higher in spinach as compared to the later treatments (AC and/or CC) ($P<0.05$). Total N uptake from OD material was also significantly higher ($P<0.05$) than AC or CC, especially in case of spinach (Table 3). Overall pattern observed in both vegetables in case of N uptake was in the order: ANC>OD>CC>AC.

Table 3. Dry mater (DM) yield and nitrogen (N) uptake by carrot and spinach. Values followed by different letters within a column are significantly different from each other.

Treatment	DM yield (g m ⁻²)			DM of root % of total	N uptake (g m ⁻²)			N uptake by root % of total	NUE ^a
	Roots	Shoots	Total		Roots	Shoots	Total		
Carrot									
Control	67.9 c	27.6 b	95.5 c	71.0 ab	0.75 d	0.30 c	1.05 d	71.03 ab	91.23 a
AC	113.7 b	58.6 a	172.3 b	66.0 b	1.27 c	0.65 ab	1.92 c	66.00 b	89.95 a
CC	116.8 b	51.6 a	168.4 b	69.4 ab	1.34 c	0.59 b	1.93 bc	69.37 ab	87.64 a
ANC	156.2 a	55.5 a	211.7 a	73.8 a	2.07 a	0.74 a	2.81 a	73.78 a	75.50 b
OD	149.6 a	52.4 a	202.0 a	73.9 a	1.71 b	0.60 b	2.30 b	73.91 a	88.41 a
Spinach									
Control	66.5 c	121.5 b	187.9 d	35.1 b	0.78 c	1.42 b	2.20 d	35.15 b	85.67 a
AC	102.1 bc	178.2 a	280.2 c	36.2 b	1.64 bc	2.95 a	4.59 c	36.20 b	61.15 bc
CC	108.7 bc	164.3 ab	273.0 c	39.8 ab	1.91 b	2.89 a	4.79 c	39.82 ab	56.90 c
ANC	174.7 a	224.7 a	399.4 a	56.4 a	3.75 a	2.88 a	6.64 a	56.35 a	60.26 bc
OD	138.9 b	214.7 a	353.7 b	39.3 ab	2.19 b	3.39 a	5.58 b	39.30 ab	63.48 b

^aN use efficiency (kg DM production per kg N uptake)

3.3.2. Total plant N recovery

Total plant N recovery both as a fraction of field applied N (TNR_p) and collected N from the filth depots (TNR_c) are presented in Figure 2a and 2b, respectively. Results revealed that composting methods had a significant effect of both these N recovery fractions ($P < 0.05$). Among the compost materials, values of TNR_p were highest from ANC material and least in case of AC (36 and 45% for carrots and spinach, respectively, vs. 17 and 24% of the applied total N, $P < 0.05$).

The latter waste type was not significantly different from CC ($P > 0.05$). When N losses during composting phase were taken into account to arrive at apparent N recovery as a fraction of collected N from the filth depots, about 31% in carrots and 39% in spinach ended up from ANC material. The respective fractions in case of AC material was only 9 and 12%, whereas 17 and 22% from OD material.

Interestingly, TNR_c values were more than three-folds greater from ANC as compared to AC and CC material for spinach (31 vs. 9 or 7%) and carrot (40 vs. 12 or 10%, Figure 2b).

Figure 1a-b Net recovery of total N as a fraction of (a) field applied compost-N and (b) collected N in MSW from filth depots. Error bars represent standard error ($\pm$) of the mean. Data bars with same texture but carrying different letters are significantly different from each other.

3.3.3. Nitrogen mineralization

Calculations of the net N balance over the experimental period have shown significant differences ($P < 0.05$) among the compost materials (Table 4). All the composting materials showed net N mineralization, however the values were highest from ANC and lowest from AC materials ($P < 0.05$). Of the total organic N applied to spinach, about 12, 15, 26, and 42% was mineralized during the experimental period from AC, CC, OD and ANC material. The respective fractions in case of carrots were 19, 16, 25 and 41% (Table 4). The difference between AC and CC was not significant in both the vegetables ($P > 0.05$). Interestingly, OD showed significantly greater N mineralization from both these waste types.

Table 4. N balance based on N applied, N uptake and final mineral N in soil. Values followed by different letters within a column are significantly different from each other.

Treatment	N applied			N Uptake by vegetables		Final Mineral N in Soil		Net recovery of Organic N	
	Total	Mineral	Organic	Total	From Compost	Total	From Compost	A ^a	B ^b
	g m ⁻²			g m ⁻²		g m ⁻²		g m ⁻²	%
Spinach									
Control	0			2.20		0.52			
AC	9.99	1.68	8.31	4.59	2.39	1.06	0.54	0.97 c	11.97 c
CC	9.91	1.53	8.38	4.80	2.60	0.86	0.34	1.23 c	14.69 c
ANC	9.99	1.02	8.98	6.64	4.44	0.68	0.17	3.73 a	41.61 a
OD	9.98	1.32	8.66	5.58	3.38	0.77	0.25	2.21 b	25.57 b
Carrot									
Control	0			1.05		0.29			
AC	4.99	0.84	4.15	1.92	0.87	0.83	0.54	0.80 c	19.37 c
CC	4.95	0.77	4.19	1.93	1.05	0.48	0.19	0.69 c	16.39 c
ANC	4.98	0.51	4.47	2.81	1.70	0.83	0.54	1.82 a	40.62 a
OD	4.99	0.66	4.33	2.30	0.87	0.68	0.39	1.08 b	24.93 b

^a[(N uptake from compost+ final mineral N from compost in soil)-mineral N applied in compost] ^b[(A/applied organic manure N)×100]

4. Discussion

4.1. Chemical changes and dry matter, carbon and nitrogen losses during composting

Composting of MSW can be a promising approach to deal with the problem of MSW management and the growing need for fertilizer inputs especially in developing countries such as Pakistan where increase in annual chemical fertilizers demand is about 13% (Pakistan Bureau of Statistics, 2016). Organic matter, when subjected to various storage techniques undergoes microbial changes, chemical transformations and natural losses to surrounding environment that results in DM and nutrient losses (Chadwick 2005; Shah *et al.*, 2016 a,b). For that purpose, we evaluated four composting methods and found their diverging response on DM, C and N losses during composting phase (Figure 1). All these losses were highest from CC and lowest in case of ANC heaps. This increased losses in the former case can be ascribed to (i) frequent turnings, which stimulated the aerobic degradation and resulted in release of ammonia, di-nitrous oxides, di-nitrogen, carbon dioxide and methane gases (Parkinson *et al.*, 2004; Shah *et al.*, 2012, 2016a,b) and (ii) the additional microbes introduced through animal wastes which resulted in higher microbial activity and thereby the losses (Chadwick 2005). The least losses in case of ANC were attributed to the enclosed system which blocked the air circulation, which thus resulted in least production of gases and created physical barrier for emissions. Additionally, leaching losses were prevented due to the (i) anaerobic conditions and thus restricting nitrate production and (ii) absence of direct rain exposure of the waste material (Parkinson *et al.*, 2004; Shah *et al.*, 2012, 2016a). For OD heaps, DM, C and N losses were found in between the ANC and AC treatments. This can be due to the partial aerobic and anaerobic conditions in OD. The upper layer of heaps

was partially aerobic as a result of air circulation through vegetable scraps and crop residues, whereas the inner layer of heaps would have been anaerobic due to the absence of turning operation in this treatment (Sagoo *et al.*, 2007; Shah *et al.*, 2016a). Visual observation revealed that OD heaps were subjected to weather conditions (i.e. rain, ambient temperature) that resulted in the formation of a surface coating that acted as a physical barrier to gaseous losses.

Composting techniques not only affected the DM, C and N losses but also the characteristics of the end product such as pH, N content, mineral N, EC, and C:N ratio. ANC decreased pH due to the acid formation (volatile organic acids, fatty acids) as a result of anaerobic condition (Pham *et al.*, 2012; Zhang *et al.*, 2014). However, in case of CC pH was increased by 0.16 (8.07 vs. 8.23) due to the breakdown of organic acids as described by Shah *et al.* (2012). Also, we found highest EC in the CC wastes as compared to the other materials. This might be due to the addition of manure with MSW during CC since the former contain significant amounts of dissolved salts. It can also be due to formation of inorganic compounds and increase in ions concentrations due to greater OM degradation and mass loss during composting period (Bustamante *et al.*, 2008). Further the OM content was an important parameter studied, as it contains readily and slowly degradable, and stable organic compounds. During composting degradable portions breakdown resulting in C losses as observed in form of C losses (Figure 1).

The remaining part is stable organic matter that have been reported to have the potential of binding C with soil when applied on land for 100-1000 years resulting in considerable reductions of CO₂ emissions to the atmosphere (Boldrin *et al.*, 2009; Favoino and Hogg 2008). Therefore, it can be concluded that ANC containing higher OM content would result in considerable C trapped in soil when applied to field. Masunga

et al. (2016) have reported that lesser C:N is an indication of good quality compost that contains more N to sustain microbial growth and crop yield. More C:N ratio in compost when applied to soil results in N robbing of the soil as excess C utilizes the soil N to bind the cell protoplasm. However, too low C:N ratio does not improve the soil structure, therefore, C:N ratio less than or equal to 20 is considered desirable (Varma and Kalamdhad 2013). In accordance with the aforementioned findings, C:N ratio in this experiment was lesser than 20 in case of ANC and CC treatments.

4.2. Nitrogen fertilizer value

Effect of composts application on vegetable yield was very clear and significantly different among the treatments. Improvement in biomass and yield of carrot and spinach in MSW compost amended soil in comparison to control soil was observed. Similar trend in these parameters have already been observed in rice (Bhattacharyya *et al.*, 2003), spinach (Maftoun *et al.*, 2005), strawberries (Hargreaves *et al.*, 2008a), timothy and red clover, (Zheljzakov *et al.*, 2006), wheat (Bar-Tal *et al.*, 2004), and maize (Carbonell *et al.*, 2011). Among the compost materials, yield and N uptake was the highest from ANC material (Table 3). This can be due to the relatively greater mineral N content and presence of more readily mineralizable organic N fractions in ANC than other treatments (Shah *et al.*, 2013, 2016a,b; Thomsen, 2001). This was reflected in greater net N mineralization rate of ANC as compared to the other waste types (Table 4). Calculations of net N balance revealed that about 40% of the organic N in this material was mineralized during the experimental period. On the other hand, least N mineralization was found from AC and CC materials (Figure 2a-b). This can be associated with: (a) loss of readily degradable N during the composting phase; and (b) transformation of available N into

stable forms leading to lower N mineralization when applied to soil (Shah *et al.*, 2016a,b; Thomsen, 2001). This together with relatively lower inorganic N content resulted in lower N recovery from AC and CC material (Figures 2a-b). These results corroborates with Shah *et al.* (2013) and Shah *et al.* (2016a) who also found relatively lower N mineralization and crop N recovery from aerobically composted as compared to anaerobically composted solid cattle manure. Organic-N mineralization is an important factor that affect the nutrient uptake from organic amendments significantly (Masunga *et al.*, 2016). Fertilizer value of treatment is evaluated on the basis of mineral N available at the time of application and mineralizable organic N available in treatment applied, and more recovery of N is associated with more availability of readily mineralizable organic N compounds (Shah *et al.*, 2013). Therefore, N recovery from applied treatments was calculated and it was higher in case of ANC i.e. 36% in case of carrots and 45% in case of spinach that is also a positive aspect of ANC as given in Table 3 and 4 that provides an evidence of good fertilizer value of ANC in comparison with other treatments. When total N losses during composting stage were included in the calculations to arrive at the fraction of N collected from the filth depots, the plant recovery N fractions were more than three times higher in ANC treatment as compared to traditional AC and CC methods. Consequently, a greater amount of the collected N ended up in plants and increasing the N cycling through waste-soil-plant continuum. In organic agriculture, where the use of artificial fertilizers is prohibited, it is essential to recycle N to soil and therefore ANC composting is superior in this regard. Relatively greater N mineralization, from ANC material than AC or CC material, indicate preferences by the soil biota community for the former material, in all probability due to the greater fraction of easily degradable compounds. In addition, more degradable

compounds will remain in MSW stream after ANC as compared to AC or CC. This implies that ANC strategy will also have more scope in improving soil biology and functioning, which in turn can increase the soil fertility and thereby on-farm N cycling through the waste-soil-plant continuum as compared to the traditional composting methods (Shah *et al.*, 2013, 2016a,b).

N recoveries from all the composted material were relatively greater in case of spinach as compared to carrots. Similarly, spinach total yield was also higher than carrot. Civeira (2010) reported that when MSW compost was applied, higher organic C, nutrients contents and superior physical properties in the topsoil resulted in higher shoot growth since in their work aerial biomass was twice as greater than observed in control. Similar may have been the case in the present study where spinach being a leafy vegetable have taken up more N and resulted in more yield while carrot being a root vegetable have shown comparatively lesser yield and N recovery.

5. Conclusions

Results of this study revealed that total C and N losses can be reduced remarkably by anaerobic composting (AC) of municipal solid waste. The waste composted under this technique had great mineral N content and mineralizable organic N fractions. Consequently, N mineralization, vegetable N uptake and yield were the highest in this case. This all resulted in almost twofold greater vegetable N recovery of the field applied N as compared to aerobic (AC) and co-composting techniques (CC). When total N losses were taken into account to calculate vegetable N recovery as a fraction of N collected from the filth depots, the respective difference increased to more than threefold. All these findings led us to conclude that anaerobic composting (AC) of municipal solid waste is superior to the other

conventional composting techniques from view point of N cycling in agro-ecosystems. Adopting this strategy in the MSW management stream in the developing countries could have win-win situation: recycling of plant nutrients through waste-soil-plant continuum and minimization in the amount of MSW production. This can have a wide scope, especially in Pakistan, because of (i) unavailability of artificial fertilizer to resource poor small landholders due to high prices, and (ii) increased trends towards organic farming. According to an estimate, Pakistan have 10 times more N in organic sources (mainly from FYM and MSW) than is currently being used through synthetic fertilizers (www.parc.gov.pk). Thus, recycling of this N in agriculture is crucial to develop sustainable agriculture.

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