Effect of particle size on rotary drum composting of garden waste and their ranking using analytical hierarchy process

Sandeep Mishra (✉ itssandeepmishra@gmail.com)

SVNIT: Sardar Vallabhbhai National Institute of Technology <https://orcid.org/0000-0001-5177-2594>

Kunwar D Yadav

SVNIT: Sardar Vallabhbhai National Institute of Technology

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Abstract

Garden waste comprises of 15–18% fraction of total municipal solid waste generated. For composting of garden waste, particle size is an important factor for efficient degradation. The present study investigates role of varying particle size on compost quality. The garden waste was grinded using a shredder into varying size of particles, 0.5–1.5, 1.5–3.0, 3.0–4.5 and 4.5–7.5 cm diameter named as R1, R2, R3 and R4 respectively. 100 kg of garden waste mixed with 20 litre cow-dung slurry and 10 kg fresh compost and feed into the rotary drum for 45 days composting period. Thermophilic phase continued for 7, 8, 4 and 3 days in R1, R2, R3 and R4 reactor respectively. Total volatile solids reduction was 29.10, 31.20, 24.23 and 17.12 %, CO₂ evolution rate was 4.92, 4.14, 6.18 and 8.16 mg/gVS/d, C/N ratio was 16.91, 15.05, 18.13 and 20.99, germination index was 92.00, 94.12, 85.21 and 81.20 in R1, R2, R3 and R4 reactor respectively after end of composting period. Reduction of hemicellulose, cellulose, and lignin was highest in R2 drum and lowest in R4. The percentage reduction of acid insoluble lignin was 36, 39, 29 and 27 % and the percentage reduction of acid soluble lignin was 48.85, 52.89, 43.39 and 36.97 % in combinations in R1, R2, R3 and R4 respectively after 45 days. As per analytical hierarchy process, performance of reactors was observed in the following trend, R2 > R1 > R3 > R4. Particle size range 1.5–3.0 cm diameter showed optimum size for efficient composting of garden waste.

1. Introduction

The increase in global urban green areas has led to rise in total garden waste (GW) generation (Reyes-Torres, Oviedo-Ocaña, Dominguez, Komilis, & Sánchez, 2018a). In developing and developed nations, this has become an environmental concern (L. Zhang & Sun, 2016b). GW comprises of 15–18% fraction of total municipal solid waste generated (Kumar et al., 2010; Manu et al., 2013; Wei et al., 2017). GW is a low density (50–75 kg/m³), heterogeneous mixture, occupying more space (Eades, Kusch-Brandt, Heaven, & Banks, 2020) and with a low decomposition rate (Reyes-Torres et al., 2018a). In India, around 1130 million tons per year is the total annual production of leafy biomass (Bhange, Prince, Vaidya, & Chokhandre, 2014). Shi et al., (2013) and Macfarlane, (2009) emphasized about GW being potentially large and an underutilized resource for an alternative source of energy. GW usually consists of coarse and fine fractions. The coarse fraction (e.g. >50–150 mm diameter) mostly consists of recalcitrant wood and bark and is used in incineration for power generation (Haynes, Belyaeva, & Zhou, 2015b). Also, medium-ranged GW (20–50 mm diameter) is mostly used as a garden mulch or used in compost fraction (Bhange et al., 2014). The majority of fine fractions consisting of leaves, small branches, twigs, flowers, and soil particle residues are used for composting along with easily degradable co-composts (Slater and Frederickson, 2001; Adams et al., 2008; Belyaeva and Haynes, 2012).

Extensive research has been documented on different disposal methods of GW (Shi et al., 2013; Bustamante et al., 2016; Reyes-Torres et al., 2018b). GW has been utilized as a feedstock for composting or co-composting methods (Bart Vandecasteele, Boogaerts, & Vandaele, 2016) and even for the production of energy (Shi et al., 2013). Although, composting is a biological method where microbes responsible for stabilisation of organic waste are naturally available, addition of inoculating agents and bulking agents helps in faster degradation of GW and quality of compost is also improved (Karnchanawong and Nissakla, 2014a; Smith et al., 2006; Xu and Li, 2017). Wei et al., (2017) highlighted the suitability of GW for composting as compost obtained has valuable organic amendments for the soil. Also, GW has low micro-pollutants content which makes it beneficial for organic farming and at household level (Bustamante et al., 2016; Zhang and Sun, 2016). Effects of various co-substrates (fly ash, phosphate rock, jaggery, bio-char, pig manure and wood chips) used with GW for composting has been reported by several researchers (Belyaeva and Haynes, 2012; Bustamante et al., 2016; Dzulkurnain et al., 2017; Francou et al., 2008; Gabhane et al., 2012a; Kumar et al., 2010; Wang et al., 2004; Reyes-Torres et al., 2018c; Zhang and Sun, 2016a).

In broad terms, factors affecting GW composting can be categorised into two groups, firstly, depending upon the composting mix formulaton, such as particle size, pH, moisture and porosity and secondly, depending upon the process management, such as compaction, water content, rate of aeration, and temperature (López et al., 2010). Also, the control on key point indicators (KPI) or parameters are crucial as they give idea about optimal process conditions (Eades et al., 2020). Rise in temperature during initial 15 days promotes sanitisation of waste (Manu et al., 2013). Moisture is important to promote microbial activities for degradation of organic waste (Pettitt et al., 2010). The C and N are critical for microbes as they are structural element and source of energy (Epstein, 2011). pH of feedstock and acid production during initial stages of composting supports appearance of certain groups of microbes and affects organic matter transformation (Sundberg & Jönsson, 2008). Maturity and stability parameters such as C/N

ratio, CO₂ evolution rate and germination index are important indices to assess quality of compost and its practical usage in agriculture (Mondini, Fornasier, & Sinicco, 2004).

In-vessel composting has several advantages over the traditional method of composting. It requires less space for operation, disruption due to weather changes is avoided, and GW can be mechanically turned or mixed (Sangamithirai, Jayapriya, Hema, & Manoj, 2015). Also, problem of fly breeding and rodents are eradicated because of close and intact design (Chang, Tsai, & Wu, 2006; Pradhan, Arora, & Mahajani, 2018). Similarly, it has better control of environment factors such as temperature, moisture and airflow (Hogland & Marques, 2003). Among various in-vessels systems available, the rotary drum composter is an proven reactor for the effective degradation of organic waste (Varma and Kalamdhad, 2015). Gajalakshmi and Abbasi, (2008) have also reported various advantages of rotary drum when compared with other method of composting. Rotary drum facilitates adequate agitation, sufficient aeration, and proper mixing of the waste, and time of degradation is drastically reduced to 2–3 weeks (Kalamdhad & Kazmi, 2009). Rotary drum can be designed as per the requirement of total waste generation. Also, rotary drums can be upgraded to manage continuous flow of waste for diverse type of organic waste such as chicken litter, vegetable waste, food waste, municipal biosolids, swine manure and cattle manure (Smith et al., 2006; Aboulam et al., 2006; Kalamdhad and Kazmi, 2008; Tolvanen et al., 2005; Varma and Kalamdhad, 2015). Among in-vessel composting, rotary drum being totally enclosed, quicker and efficient due to daily turning and breaking of organic matter offers many advantages when compared with traditional method (Varma, Kalamdhad, & Kumar, 2017). Owing to daily rotation and aeration, degradation of compost progress at much faster rate than static bin or windrow composting (Alkoik, Abdel-Ghany, Rashwan, Fulleros, & Ibrahim, 2018).

Cow dung is a rich source of microflora and very effective in organic waste degradation (Randhawa and Kullar, 2011; Rastogi et al., 2019). Singh and Kalamdhad, (2013) in his composting study used a rotary drum for a mixture of saw dust, vegetable waste, and cow-dung in composting. Zhang and Sun, (2016b) improved the nutrient content and C/N ratio of the compost by co-composting garden waste with cow-dung. Use of cow-dung slurry in a 1:10 or 1:25 ratio can also help in degradation of rural, urban, hospital waste, and even oil spillage (Randhawa & Kullar, 2011).

Recently, researchers have included compost in their feedstock material to promote faster degradation of biomass (K. K. Gupta, Aneja, & Rana, 2016). Ohtaki et al., (1998) studied that adding compost in feedstock could enhance conversion of organics, increase the numbers of microbes and even reduce odorous gas emissions. Compost as a feedstock contains active microbial population required for transformation of organic matter into humus like substance (Karnchanawong & Nissaiakla, 2014). The heat microbes produce causes the compost temperature to rise rapidly. Microbes release hydrolytic enzymes which breaks complicated structured molecules promoting faster degradation (Rastogi et al., 2019).

Particle size is also an important factor for the efficient degradation of GW. Smaller particle size leads to larger surface areas and makes it easier for bacteria to degrade effectively as the majority of the bacterial invasion occurs on or near the surface (Lata Verma & Marschner, 2013). Particle size distribution of the feedstock material effects degree of compaction and porosity favouring aeration of materials (Liu, Wang, Guo, Zhao, & Zhang, 2017). Larger size of particles hinder rise of feedstock temperature and smaller size of particles hinder pore formation (Bernal et al., 2009; Onwosi et al., 2017; Zhou et al., 2014). As per Duong et al., (2012) finer composts release more nitrogen and phosphorous as compared to coarse composts, and grinding of feedstock increases the degradation rate by a factor of two. Also, they recommended the particle size varying between 1.3–7.6 cm diameter, where a continuously mixed system was suggested for the smaller particle size range and a windrow system of composting suggested for the larger particle size range. Zhang and Sun, (2014) assessed varying particle size (i.e. 10, 15 and 25 mm) during co-composting GW and rhamnolipids and found increase in total N content and reduction in C/N ratio as compared to control for 15 mm particle size. Also, as per Ayilara et al., (2020) particle size range 1 to 2 inches in diameter gave best composting conditions. Zhao et al., (2017) during their study found that rate of aerobic decomposition increases as the particle size decreases and revealed that finest degradation for tobacco leaves composting was achieved with particles sized at 25 mm. Haynes et al., (2015a) found that N mineralization potential, nutrient content and decomposition rate of GW is influenced by varying particle size. Doublet et al., (2010) and Fangueiro et al., (2010) studied the relationship between C and N dynamics and particle size of compost. Also, as per Fangueiro et al., (2010), N mineralization was higher C/N ratios lower in fine fractions when compared with coarse fractions.

Particle size reduction homogenizes and reduces waste volume, and surface area of feedstock is increased promoting faster degradation of recalcitrant substances (Hannon & Mason, 2003). Particle size reduction can be carried out by shredding or grinding of waste, particularly fibrous materials such as leaves, small branches, twigs, flowers, grass, and other minor parts of garden waste. Shredding leads to uniformity in composting, adequate aeration, and proper maintenance of moisture (Rinkes, DeForest, Grandy, Moorhead, & Weintraub, 2014).

Composting of GW supports concept of circular economy as GW is reduced and its nutrients recycled back into fertilisers to feed diverse life of soil rather than increasing the MSW waste into already exhaustive landfills (Bai, Shen, & Dong, 2010). Composting of organic waste promotes waste reduction and is promoted by European Union Waste Directive 2008/98/EC (EP&C, 2008). GW composting advances the goals of EU Directive 2009/28/EC in promotion of renewable energy (EP&C, 2009), which obliges EU Member States to recover 20% of total energy needs through renewable sources of energy. Also, use of compost in agriculture supports target objectives to reduce 50% of organic waste going into landfills by 2050 (Pergola et al., 2020). GW composting also supports Paris agreement as biomass utilization contribute to the reduction in greenhouse gases (Ollila, 2019).

Analytical hierarchy process (AHP), a decision-making method has been widely used in various fields to solve multi-criterion selection problem (Sharma & Yadav, 2018a). AHP allows decision-makers to set their priorities and make the best selection of both tangible and intangible aspects (Md Zaini, Basri, Md Zain, & Saad, 2015). Sharma and Yadav, (2018a) used AHP for selection of best ratio of mix for composting of flower waste. Curiel-Esparza et al., (2014) used AHP for selection of a sustainable disinfection technique for wastewater reuse projects. Md Zaini et al., (2015) used AHP for selection of best composting technology for solid waste management. Widespread study has been done on composting but rarely any study has discussed the effect of varying particle size on the composting of garden waste using AHP method.

Understanding particle size distribution and their role in various processes are important for many manufacturing industries as particle size have a direct influence on product properties such as reactivity or dissolution rate, stability in suspension, the efficacy of delivery, flowability, and handling (Gao et al., 2010; Wang and Ai, 2016). Also, particle size fraction and their shape affect the operational cost of sieving (Y. Wang & Ai, 2016). Use of GW compost as fertiliser will increase physical structure of soil, increased crop and yield and water holding capacity of soil also increases. (Vivas et al., 2009 ; Bhagwat et al., 2011). The present study is aimed to investigate the scientific way for the disposal of garden waste and to determine the role of different particle size on compost quality. The AHP method was used to rank the drums by selecting the physico-chemical and maturity indices of the compost.

2. Materials And Methods

2.1. Study site

The experiment was conducted at Solid waste laboratory, *Sardar Vallabhbhai National Institute of Technology (SVNIT)*, Surat, Gujarat, India. The site is located at 21.17 °N latitude and 72.83 °E longitude. Surat has a tropical savanna climate, and the average temperature varies between 27°C to 31 °C.

2.2. Raw materials

The experiment was performed using garden waste (100 kg) along with cow-dung slurry (20 litre), and compost (10 kg). In the present study, garden waste was collected from Jawahar Lal Nehru garden, Athwa gate, Surat, Gujarat in month of September-October, 2019. The waste represented the homogenous mixture of varieties of tree species but the majority of them include fallen leaves (brown and green), grass, small branches, sticks, and others. The garden waste brought was thoroughly mixed and unwanted materials (wrapping papers, plastics, cans, and sticks) were removed manually during sorting of GW. For composting, small branches and twigs that contained most of the woody part were also removed. The GW was homogenized by shredding. The garden waste was shredded into R1 (0.5-1.5 cm diameter), R2 (1.5-3 cm diameter), R3 (3-4.5 cm diameter) and R4 (4.5- 7.5 cm diameter) particle size range using leaf cutter/pulveriser. The shredder consisted of a mainframe with adjustable slots with varying pore size for shredding of garden waste.

Fresh cow-dung was collected at the start of composting process using a 20-litre plastic bucket from Umra village, near SVNIT, Surat. 10 litre cow-dung was mixed with 10 litres of water and converted into a slurry.

Fresh compost was prepared in the SVNIT laboratory by using flower waste as feedstock. Rotary drum was used to prepare fresh compost. Fresh cow dung and compost were added only during the start of the composting process. Cow-dung and compost used acted as a source of microbial biomass to enhance the degradation of GW. The physico-chemical characteristics of all raw materials are given in Table 1.

Table 1. Initial physico-chemical characteristics of feedstock material, n (no. of samples) =3

Parameters	Unit	Garden waste	Cow dung	Compost
Moisture content	(%)	46.12 ± 1.44	90.82 ± 1.52	44.04 ± 1.63
Total organic carbon (TOC)	(%)	44.02 ± 0.83	32.11 ± 0.67	23.42 ± 0.92
Total volatile solids (TVS)	(%)	80.55 ± 0.84	58.76 ± 0.37	42.39 ± 0.21
Ash content	(%)	19.21 ± 0.43	40.22 ± 0.67	55.0 ± 0.84
Potassium (K ₂ O)	(g/kg)	0.25 ± 0.02	10.0 ± 0.22	28.52 ± 0.42
Phosphorous (P ₂ O ₅)	(g/kg)	0.13 ± 0.07	2.78 ± 0.18	22.21 ± 0.75
pH	-	6.93 ± 0.23	6.87 ± 0.12	7.43 ± 0.12
Electrical conductivity (EC)	(mS/cm)	1.52 ± 0.12	3.44 ± 0.18	2.87 ± 0.13
Total nitrogen (TN)	(%)	1.64 ± 0.12	1.41 ± 0.14	2.01 ± 0.18
Ammoniacal Nitrogen	(mg/kg)	181.14 ± 1.72	0.34 ± 0.03	75.67 ± 1.36
C/N ratio	-	26.83 ± 0.67	22.81 ± 0.41	14.56 ± 0.22

2.3. Reactor Configuration and design- Rotary drum

Fig. 1 shows a rotary drum composter with a capacity of 0.6 m³. The drum measurements were the following: length-1.20, diameter- 0.80 m and thickness of metal sheet- 0.3 mm. To keep the drum rust-free, inner parts were painted with anti-corrosive paint (red oxide). The angles were welded longitudinally for an enhanced mixture of waste inside. Two holes of 10 cm were made into the bottom of the drum to drain off leachate, if any. A metallic stand was fabricated for the proper installation of the drum. Roller and chain were used for the rotation of the drum. Air enters naturally from both half side open parts of the drum and is mixed with the waste as it tumbles. The waste gets mixed, aerated and agitated during the rotation of drum.

2.4 Methodology

The present study was conducted to monitor the changes in physico-chemical parameters of R1 (0.5-1.5 cm diameter), R2 (1.5-3 cm diameter), R3 (3-4.5 cm diameter) and R4 (4.5- 7.5 cm diameter). Rotary drums were used for composting of garden waste (100 kg) along with cow-dung slurry (20 litre), and compost (10 kg). The ratio was selected as per information available in the literature for maximum degradation. Materials were feed into four different rotary drums and the experiment was run for 45 days. In rotary drums, the temperature was observed every day using a digital thermometer (Mextech ST9283B Multi Stem Thermometer) and all other parameters were recorded at three days interval. The temperature was observed at six different locations of the reactor and its average value was recorded. The addition of water was done on a dry weight basis to maintain the moisture level between 50-60% during the entire study period.

The rotary drum composter was rotated manually. Manual turning was carried out after every 24 hours by rotating it thrice in clockwise and then anti-clockwise direction for proper mixing. Approximate 300 grams per sample were collected from the centre and two extremities (top, middle, and bottom) from all reactors after every 3 days. Total Volatile solids, CO₂ evolution rate,

germination index and temperature are most important indicators to reflect composting performances. All parameters were immediately analysed after collection of samples or stored in the deep freezer for further analysis

2.5 Analysis of physico-chemical parameter

Moisture content was calculated in a hot air oven by drying the sample at $70 \pm 2\text{ }^{\circ}\text{C}$ for 24-72 hours. Ten grams of oven-dried powdered sample, diluted with 100 ml distilled water (1:10 w/v), and then rotated in a rotary shaker for 120 minutes and kept for 60 minutes to let it settle down and subsequently filtered using Whatman filter paper no. 42 to find pH and electrical conductivity. Kjeldahl approach was used to determine total nitrogen. KCl extraction procedure led by the phenate method (APHA, 2005) was used to determine ammoniacal nitrogen. Total volatile solids was calculated by burning the oven-dried sieved samples at $550 \pm 5\text{ }^{\circ}\text{C}$. Also, as per Adhikari et al., (2009), TOC (Total Organic Carbon) was calculated by dividing the volatile solids by 1.83. CO_2 evolution rate was found using the lime-soda method as per Singh and Kalamdhad, (2014). For phosphorous analysis, 0.2-gram sample was digested using a heating digester (Velp Scientifica DK 20) with 10 ml H_2SO_4 and HClO_4 for 2 hours at $300\text{ }^{\circ}\text{C}$ in 5:1 ratio and then stannous chloride was used to find phosphorous concentration. Potassium concentrations were found using a flame-photometer (Systronics 128I) by digesting 0.2 gram oven-dried sieved sample with 10 ml HClO_4 and H_2SO_4 for 2 hours at 300°C in the ratio 5:1 (Jain, Daga, & Kalamdhad, 2019). For determination of germination index, 50 gm compost sample was taken at 3 days interval and mixed into 100 mL distilled water and kept in shaker for 6 hours and subsequently centrifuged for 20 min. at 8000 rpm. Five ml centrifuged sample quantity was taken into each petri dish, and 5 mL deionized water for control. Also, ten radish seeds were sown with 10 replicates per treatment. The petri dish was incubated for 72 hours at 25°C . After 3 days, GI was calculated as per given formula (Sangamithirai et al., 2015).

See formulas 1 and 2 in the supplementary files.

Lignin measurement was performed by taking 3 g of powdered sample and digested using 72% H_2SO_4 and the extract was filtered. Absorbance at 205 nm was performed to calculate the acid soluble lignin from the filtered sample by drying the filtrate at 105°C . The difference of acid soluble lignin and acid insoluble lignin was taken according to National Renewable Energy Laboratory procedure (NREL; Templeton and Ehrman, 1995; Sluiter et al., 2008). Cellulose was determined by the acetic/nitric reagent extraction method as reported by (Updegraff, 1969), and hemicellulose was calculated from the difference between the natural detergent fiber (NDF) and acid detergent fiber (ADF) using the method provided by Goering and Van Soest (1970).

2.6 Analytical Hierarchy Process

AHP has been widely used for performing qualitative and quantitative numbers using appropriate scales to convert qualitative values in absolute numbers. Since, varying attributes have varying dimensions, normalisation is done to make attributes dimensionless. In the present study, geometric mean method is used as it is easier to understand (Ghaitidak & Yadav, 2015). In this method, eigenvalues are determined easily reducing the inconsistencies in judgement (Sharma & Yadav, 2018a). The intensity of attributes was decided after taking several opinions of experts (Table 2).

Table 2. Description and importance of nine-point intensity scale

Definition	Intensity of importance
Equally preferred	1
One is Moderately preferred over another	3
One is strongly preferred over another	5
One is very strongly preferred over another	7
One is extremely preferred over another	9
Intermediate values	2,4,6,8

Source: Ghaitidak and Yadav,(2015)

2.7 Statistical analysis

ANOVA of physico-chemical parameters is shown in Table 3. All the physio-chemicals parameters monitored represent the average of the equivalent. One-way ANOVA was used for all the physicochemical parameters analysed during composting. SPSS 13.0 was used for all single parameters in all the drums to compute the variance (i.e., ANOVA $p < 0.05$). The objective of the statistical analysis was to observe significant variations among all monitored parameters for all combinations of drums.

Table 3. Anova of physico-chemical parameters.

Parameters	Anova	Sum of squares	Degree of freedom (DF)	Mean square	F-value	p-value
pH	Between groups	0.51	3.00	0.17	2.89	0.0423
	Within groups	17.26	60.00	0.29		
	Total	17.76	63.00			
Electrical conductivity	Between groups	0.28	3.00	0.09	3.453	0.0261
	Within groups	3.16	60.00	0.05		
	Total	3.45	63.00			
Total organic carbon	Between groups	170.04	3.00	56.68	3.55	0.0019
	Within groups	956.61	60.00	15.94		
	Total	1126.64	63.00			
Ammoniacal nitrogen	Between groups	4889.51	3.00	1629.84	3.88	0.013
	Within groups	52017.99	60.00	866.97		
	Total	56907.50	63.00			
Total Nitrogen	Between groups	0.21	3.00	0.07	2.865	0.0438
	Within groups	1.71	60.00	0.03		
	Total	1.92	63.00			
Germination Index	Between groups	1202.10	3.00	400.70	8.21	0.00016
	Within groups	2929.19	60.00	48.82		
	Total	4131.29	63.00			
CO ₂ evolution rate	Between groups	86.21	3.00	28.74	2.758	0.0495
	Within groups	1228.30	60.00	20.47		
	Total	1314.52	63.00			
C/N ratio	Between groups	155.64	3.00	51.88	4.30	0.008
	Within groups	1355.97	60.00	22.60		
	Total	1511.62	63.00			

3. Results And Discussions

3.1 Temperature, Moisture content, pH and Electrical conductivity

Temperature is an important factor and decides the rate at which all processes take place inside the reactor and even influences microbial growth (Hassen et al., 2001). Fig. 2 shows the temperature variations over 45 days of the composting cycle. The ambient temperature varied from 27°C to 30°C. The temperature started rising as composting progressed and the highest temperature was

observed in R1 (72°C) followed by R2 (71°C), R3 (67°C) and R4 (65°C) on the second day itself. No significant temperature differences were observed between (R1 and R2) and (R3 and R4), however, temperature differences were observed between R1 and R3. Thermophilic phase continued for 7, 8, 4 and 3 days in R1, R2, R3 and R4 reactor respectively. It was observed that in all the reactors, the temperature of garden waste showed a constant trend after 22 days. Higher the duration of the thermophilic phase, faster the degradation and greater the reduction in total carbon. Also, thermophilic phase is critical for sanitisation of garden waste as pathogens are killed at high temperatures (Singh & Kalamdhad, 2016). Also, high temperatures for longer duration should be avoided as it may cause undesirable chemical modifications of organic matter and slow down the microbial activity as many microbes can't survive at high temperature (Reyes-Torres et al., 2018b).

Moisture content plays critical role during the organic waste degradation. A higher reduction in moisture content was observed for first 15 days when thermophilic phase was predominant. Also, loss of moisture and the rise of temperature is an index of the rate of decomposition since microbes generate heat as they decompose (Singh & Kalamdhad, 2016). Fig. 2 gives the initial moisture content in R1, R2, R3 and R4 as 72.2, 71.54, 71.83 and 71.92% which after 30 days was reduced to 54.50, 53.10, 56.10 and 59.45% respectively. After, 30 days, addition of water was done on dry weight basis to maintain the moisture level between 50-60% for maximum survival of microbes (Razmjoo, Pourzamani, Teiri, & Hajizadeh, 2015). After 45 days, moisture reduced to 55.32, 55.18, 56.14 and 56.94 % in R1, R2, R3 and R4 respectively. The result is supported by (Wani, Mamta, & Rao, 2013a) during composting of GW, cow-dung and kitchen waste.

pH of the feed material is one of the indicators of rate of degradation. The initial pH in R1, R2, R3 and R4 were 6.43, 6.23, 6.69 and 6.24 which rose to 7.40, 7.84, 7.50 and 7.30 respectively after 15 days and dropped towards neutral after the composting period as shown in Fig. 2. No significant difference was observed concerning size of the particle from 0.5 to 7.5 cm diameter. The pH of all combinations decreased at first due to the release of organic acids and then increased and moved towards neutral at the end (Awasthi, Pandey, Bundela, & Khan, 2015). The difference in pH was due to hydrogen ions presence throughout the composting period and plays a significant role in transportation across the microbial membrane, affecting microbial activities (Paredes, Bernal, Roig, Cegarra, & Sánchez-Monedero, 1996). The rotation of garden waste in the reactor provides adequate aeration accountable for the rise in pH value and increased degradation of GW due to hydrogen ions release during aeration. The result is supported by Verma and Marschner, (2013) where garden waste compost for particle size >5 to <3 mm also showed no differences in pH values.

Electrical conductivity (EC) is an indicator of compost maturity and reflects salinity of substrates present, and is important because plant growth does not desire high salinity (Vaverková, Burešová, Adamcová, & Vršanská, 2017). EC > 12 mS /cm or higher in compost will adversely affect the growth of plants such as low germination and withering (Varma and Kalamdhad, 2015). Initial EC in R1, R2, R3 and R4 were 2.56, 2.75, 2.42 and 2.55 mS/cm which increased to 3.20, 3.50, 3.08 and 3.10 mS/cm after 15 days and then dropped towards 2.92, 2.71, 2.73 and 2.87 mS/cm respectively after 45 days of composting as shown in Fig. 2. Also, EC values within 3-12 indicate an index of compost maturity (S. Zhao, Liu, & Duo, 2012). The release of mineral salts (phosphate, ammonium ions) led to organic matter decomposition which led to an initial increase in EC. Mineral salt precipitation could be a reason for a decrease in EC in all combinations (Krishna & Kalamdhad, 2014). Also, the release of humic substance and its interaction with highly conductive exchangeable metal ions to form an insoluble complex at later phases of the composting process might have lowered the EC of the compost (Wani, Mamta, & Rao, 2013b). A similar trend in EC was observed by Zhao et al., (2012) and Sharifi and Renella, (2015). The significant difference ($p < 0.05$) in the variation of pH, electrical connectivity is indicated by ANOVA analysis.

3.2 Total organic carbon (TOC), Total volatile solids (TVS) and Ash content

TOC is an important parameter and indirect indicator of the degree of compost maturity (Awasthi et al., 2015). The initial TOC in R1, R2, R3 and R4 were 44.93, 45.70, 45.06 and 44.85 % which reduced to 31.79, 31.46, 34.18 and 37.36 respectively after 45 days as shown in Fig. 3. TOC reduction of R1, R2, R3 and R4 was 13.14, 14.24, 10.98 and 7.49 % respectively with the highest reduction in R2 and lowest in R4. A similar reduction in TOC was observed by Elango et al., (2009) and Adhikari et al., (2009) during composting of MSW and food waste. There was a declining trend in carbon content as particle size increased due to higher microbial activity at a higher temperature in reactors. The higher degradation of TOC because of active microbial metabolism at

the thermophilic stage is also supported by Kalamdhad and Kazmi, (2009). ANOVA analysis indicates the significant difference ($p < 0.05$) in the variation of total organic carbon in all the drums.

The initial total volatile solids in R1, R2, R3 and R4 were 82.23, 83.63, 82.46 and 82.07 % which reduced to 58.18, 57.57, 62.37 and 68.36 % respectively after 45 days of composting period as shown in Fig. 3. TVS reduction of R1, R2, R3 and R4 was 29.10, 31.20, 24.23 and 17.12 % respectively. As particle size decreased, volatile solids reduction increased. The high volatile solids reduction in the first 15-20 days was more in smaller particle size as compared to higher particle size. It may be due to the adequate availability of substrate to the microbes. The result is supported by Jain et al., (2019) where TVS decreased during composting of vegetable waste, cow-dung and saw-dust at thermophilic phase.

The ash content in all reactors increased when the reduction of TOC started. The initial ash content in R1, R2, R3 and R4 were 17.77, 16.57, 17.54 and 17.43 % and increased to 41.82, 42.43, 37.63 and 31.64% respectively after 45 days as shown in Fig. 3. Percentage of ash content increased as particle size reduced. Increase in ash content is an indicator of higher rate of degradation of garden waste.

3.3 Ammoniacal nitrogen, CO₂ evolution rate, Germination Index and C/N ratio

Ammoniacal nitrogen acts as an indicator of the maturity of compost. For the compost maturity, the concentration of ammonia nitrogen < 400 mg/kg is appropriate (Bohacz, 2017). The initial ammoniacal nitrogen in R1, R2, R3 and R4 were 160.34, 157.45, 160.13 and 161.45 mg/kg which decreased to 133.23, 129.67, 137.34 and 151.34 mg/kg respectively after 45 days as shown in Fig. 3. It was observed that as particle size increased, ammoniacal nitrogen also increased. During the turning, $\text{NH}_4^+\text{-N}$ was released as ammonia, thereby reducing ammoniacal nitrogen. Around 50-90% of all NH_3 losses occur during the initial duration of thermophilic composting, which coincide with high pH and high temperature (Hao & Benke, 2008)). It was observed that the $\text{NH}_4^+\text{-N}$ concentration increased during the thermophilic phase indicating higher activity of microbes which tends to decrease after thermophilic phase. The ammonia nitrogen concentration decreased due to $\text{NH}_4^+\text{-N}$ volatilization by the micro-organisms and nitrification, (Sharma & Yadav, 2018b). Rashad et al., (2010) also found similar decreasing trends of ammoniacal nitrogen during the study of organic waste composting.

CO₂ evolution rate is one of the most important indicators to check the maturity of compost. The rate of CO₂ evolution of all combinations can be considered stable when the rate of CO₂ evolution is approximately 3 to 0.001 mg/gVS/day (Kalamdhad & Kazmi, 2009). Initially, CO₂ evolution rate in R1, R2, R3 and R4 were 19.21, 20.02, 18.76 and 19.45 mg/g VS/day which decreased to 4.92, 4.14, 6.18 and 8.16 mg/g VS/day respectively after 45 days of composting process as shown in Fig. 4. It was observed that as particle size increased, CO₂ evolution rate also increased. The rate of CO₂ evolution is related to volatile compost material degradation and indicates the readily degradable composting material present in the compost sample (A. Gupta, Thengane, & Mahajani, 2018). Similar trends of carbon dioxide evolution rate was found during vegetable waste composting mixed with microbial inoculant as observed by Kalamdhad et al., (2009).

Germination index (GI), indicator of compost maturity and phytotoxicity helps to evaluate composting efficiency and is used to test the toxic effect of the compost and its suitability for agricultural purposes (Alfred, 2001). GI value greater than 80 % indicates mature compost and is phytotoxic-free (Wang et al., 2004). The initial GI values in R1, R2, R3 and R4 were 68.02, 60.18, 66.10, 64.21% which gradually increased until the end of composting process to 92.20, 94.15, 85.20 and 81.25 % as shown in Fig. 4. The final GI results confirmed that compost will have no toxic effect on plants growth. Also, a similar trend of GI was observed by Sangamithirai et al., (2015) during in-vessel composting of yard waste and also during physicochemical characterization of sewage sludge along with GW (Ramdani, Hamou, Lousdad, & Al-Douri, 2015).

The C/N ratio is the compost maturity indicator affecting the composting process and end product properties of compost (Kumar et al., 2010). Carbon is utilized as source of energy by microbes and nitrogen is used for building cell structure (Sharma & Yadav, 2017). In the present study, C/N ratio was 16.91, 15.05, 18.13 and 20.99 in R1, R2, R3 and R4 reactor respectively after 45 days as shown in Fig. 4. It was observed that as particle size increased, C/N ratio also increased. Similar values of C/N ratio was observed during the composting of food waste and GW (Kumar et al., 2010). The result of the study is supported by Zhang and Sun, (2017)

during co-composting GW with spent coffee grounds and cow dung at different proportions. ANOVA analysis indicates the significant difference ($p < 0.05$) in the variation of ammoniacal nitrogen, CO₂ evolution rate, germination Index and C/N ratio.

3.4 Total Nitrogen, Phosphorous, Potassium (N, P, K) and C/P ratio

The concentration of nitrogen is generally increased after the composting process due to organic matter loss and by activity of nitrogen-fixing bacteria (Sudharsan Varma & Kalamdhad, 2015b). In the present study, the initial total nitrogen (TN) in R1, R2, R3 and R4 was 1.39, 1.49, 1.38 and 1.37 % which increased to 1.87, 2.09, 1.88 and 1.78 % respectively after 45 days of composting period as shown in Fig. 4. TN of compost was in the following trend: R2 > R1 > R3 > R4 showing that total nitrogen increased as the particle size decreased. Also, total nitrogen also depends upon the C/N ratio of the feedstock (Sharma & Yadav, 2017). The increase in TN was due to net loss of dry weight (Kalamdhad & Kazmi, 2009). The result is supported by (Sharma & Yadav, 2017) during composting of flower waste using dry leaves as bulking material.

Phosphorous is indispensable for plant growth and used by the microorganism for body metabolism during the composting process (Shi et al., 2013). Plants absorb phosphorous in soluble forms especially hydrogen phosphate ion (HPO₄⁻²) (Sharma & Yadav, 2018b). The initial concentration of phosphorous in R1, R2, R3 and R4 were 1.53, 1.47, 1.74 and 1.68 g/kg which increased to 4.83, 5.02, 4.52 and 3.92 g/kg respectively after 45 days of composting period as shown in Fig. 5. An increasing trend of phosphorous was observed during the degradation. Loss of organic matter led to increase in phosphorous concentration (Li, Zhang, Zhang, & Xu, 2014). Zhang et al., (2013) found a similar increase in phosphorous content during the composting of dairy waste, kitchen, garden waste, and food waste. Also, Singh and Kalamdhad, (2012) observed a similar increasing trend in phosphorous concentration of water hyacinth and vegetable waste composting. Addition of phosphorous to soil promotes natural growth, stimulus tilling, and hastens maturity in plants (Ayilara et al., 2020).

A strong positive correlation was observed between C/P and C/N in all reactors, showing that composts low in N (high C/N ratio) are also low in P (high C/P ratio). The initial C/P ratio in R1, R2, R3 and R4 were 29.37, 31.09, 25.89 and 26.69 which reduced to 6.58, 6.27, 7.53 and 9.53 respectively after 45 days of composting period as shown in Fig. 5. Trends in C/P ratio in the present study is supported by Boldrin and Christensen, (2010). Fuchs and Cuijpers, (2016) reported C/P ratios from 19-119 for 6 stable composts, and a C/P ratio of 216 for an unstable compost. Frossard et al. (2002) also reported during his study that C/P ratios were between 35- 96 for 16 composts made from solid kitchen and GW, however, C/P ratio of co-composted chicken manure ranged in 15-38 (B. Vandecasteele, Reubens, Willekens, & De Neve, 2014).

In plants, potassium primarily assists in photosynthesis and also regulates the absorption of CO₂. Potassium helps in enzyme activation and is important in adenosine triphosphate (ATP) production (Takahashi, 2014). The initial concentration of potassium in R1, R2, R3 and R4 were 5.54, 5.21, 5.33 and 5.08 g/kg which increased to 9.12, 9.51, 8.75 and 8.21 g/kg respectively after 45 days of composting process as shown in Fig. 5. As particle size decreased, the concentration of potassium increased. The reason for increment of nutrients from initial to final day was organic matter degradation and net loss in dry mass. Also, concentration of potassium increased in all rotary drums due to the potassium assimilation and immobilization by microbes (Singh & Kalamdhad, 2016). Table 4 shows the changes in physico-chemical parameters during degradation of garden waste.

Table 4 Changes in physico-chemical parameters during degradation of garden waste

Parameters	Unit	R1 ^a	R1 ^b	R2 ^a	R2 ^b	R3 ^a	R3 ^b	R4 ^a	R4 ^b	Compost Standards	
								c	d		
Moisture content	(%)	72.23	55.32	71.54	55.18	71.83	56.14	71.92	56.94	35-55	35-45
Total organic carbon (TOC)	(%)	44.93	31.79	45.70	31.46	45.06	34.08	44.85	37.36	≥16	-
Total volatile solids (TVS)	(%)	82.23	58.18	83.63	57.57	82.46	62.37	82.07	68.36	-	-
Ash content	(%)	17.77	41.82	16.37	42.43	17.54	37.63	17.93	31.64	-	-
CO ₂ evolution rate	(mg/gVS/d)	19.21	4.92	20.12	4.14	18.76	6.18	19.45	8.16	<2-3	-
Germination Index	(%)	68.02	92.20	60.18	94.15	66.10	85.20	64.21	81.25	>80	
Potassium (K)	(g/kg)	5.54	9.12	5.21	9.51	5.33	8.75	5.18	8.21	0.6-1.7 (%)	≥4
Phosphorous (P ₂ O ₅)	(g/kg)	1.53	4.83	1.47	5.02	1.74	4.52	1.68	3.92	0.4-1.1 (%)	-
pH	-	6.43	7.24	6.23	7.30	6.69	7.23	6.24	7.65	6.5-8.5	5.5-8.5
Electrical conductivity (EC)	(mS/cm)	2.56	2.92	2.75	2.71	2.42	2.73	2.55	2.87	2-6	≥ 4
Total nitrogen (TN)	(%)	1.39	1.88	1.49	2.09	1.38	1.88	1.37	1.78	1.0-3.0	-
Ammoniacal Nitrogen	(mg/kg)	160.34	133.23	157.45	129.67	160.13	137.34	161.45	151.34	-	75-500
C/N ratio	-	32.33	16.91	30.67	15.05	32.65	18.13	32.74	20.99	<25	<25

^a Feedstock (Initial day), ^b Compost (Final day)

^c TMECC (2002)-Test Method for the Examination of Composting and Compost

^d FAI (2007)-The Fertilizer Association of India.

3.5 Cellulose, hemicellulose and lignin

The degradation of lignocellulose compound depends on the microbes (Hubbe, Nazhad, & Sánchez, 2010). During the process of composting the microbes first utilized the hemicellulose as the source of energy than the microbes utilize the cellulose. The microbes degrade the hemicellulose more easily as compared to the cellulose (Yu et al., 2019). The initial presence of hemicellulose in combination in R1, R2, R3 and R4 was 17.21, 17.27, 17.45 and 17.31% which was reduced to 2.93, 2.20, 4.17, 4.21 and 6.17 % at the end of 45 days It was observed that the reduction of hemicellulose was more as compared to cellulose as shown in Fig 6. The similar higher reduction of hemicellulose was reported by (Sarika et al., 2014).

The percentage reduction of cellulose was 49.21, 51.33, 41.20 and 28.89 % respectively in combinations R1, R2, R3 and R4 after 45 days. It was observed that in combination R3 and R4 the degradation rate was slow due to the formation of lump and reduction of cellulose was low as compared to remaining combinations. Figure 6 shows the variation of acid insoluble lignin and acid soluble

lignin during the composting process. Lignin is very complicated or tough structure which is highly resistant to microbial degradation (Tuomela, Vikman, Hatakka, & Itävaara, 2000). The percentage reduction of acid insoluble lignin was 36, 39, 29 and 27 % and the percentage reduction of acid soluble lignin was 48.85, 52.89, 43.39 and 36.97 % in combinations in R1, R2, R3 and R4 respectively after 45 days. The degradation of lignin mainly occurs at the thermophilic phase of the composting process. The degradation of lignin by most of the fungi produces humus, water, and carbon dioxide (Wan & Li, 2012). During the degradation of lignin, the release of energy was less which cannot be utilized by the microorganism, but the degradation of lignin produce adequate carbohydrate for the utilization of microbes, so the microbes which degrade polysaccharides also secrete ligninolytic enzymes (Tuomela et al., 2000).

3.6 Rank of drum composting using AHP

Figure 7 shows the hierarchy structure for ranking of drums. For deciding the rank of the drums using AHP method, seven criterions for maturation of compost were selected. (1) No. of days the drums were in thermophilic phase (2) pH (3) EC (4) TOC (5) germination index (6) C/N and (7) CO₂ evolution rate. The final values of drums after 45 days have been used for ranking of each drum. Using these parameters as source of quality compost, ranking of drums have been optimised using AHP method.

Attributes and alternatives are viable for decision making (refer Mat (A1)). After hierarchy’s decision, weight criteria were calculated using AHP method. Also, consistency ratio decides the acceptance of weights. The normalised value of the quantitative data is shown below. The normalized data with the weight of attributes show the ranking of alternatives. Also, Equations 3 and 4 shows steps for finding consistency index (CI) and consistency ratio (CR).

See formula 3 in the supplementary files.

where λ_{max} = maximum eigenvalue of the matrix, λ_{max} = Average of matrix A4 (see matrix A2 section) and M = order of matrix (Here, λ_{max} = 7.748 and M = 7). The consistency ratio (CR) was calculated as Equation (4).

See formula 4 in the supplementary files.

where RI (random index) depends upon the size of the relative importance matrix (Here, RI= 1.35). As per (Sharma & Yadav, 2018b), the value of CR should be less than 0.1, which satisfies the pairwise comparison matrix for criteria and validates the weights. In this case, CR = 0.092; which is CR < 0.1; which signifies that matrix is consistent and weights are valid. Matrix A1 shows the pair wise comparison matrix for the criteria shown below (Table 5).

Table 5 Calculation of consistency ratio and the result obtained using AHP

Mat (A1)							
Attributes	Temp	pH	EC	TOC	GI	C/N ratio	CO ₂
Temp	1.00	7.00	7.00	5.00	3.00	5.00	7.00
pH	0.14	1.00	2.00	0.20	0.14	0.33	0.14
EC	0.14	0.50	1.00	0.20	0.14	0.14	0.33
TOC	0.20	5.00	5.00	1.00	1.00	3.00	3.00
GI	0.33	7.14	7.14	1.00	1.00	3.00	3.00
C/N ratio	0.20	3.03	7.14	0.33	0.33	1.00	3.00
CO ₂ evolution rate	0.14	7.00	3.00	0.33	0.33	0.33	1.00

Mat (A2)	Mat (A3) = Mat (A1) * Mat(A2)	Mat (A4) = Mat(A3)/ Mat (A2)	
Temp	0.41	3.22	7.86
pH	0.03	0.02	7.86
EC	0.03	0.20	7.76
TOC	0.17	1.24	7.51
GI	0.20	1.42	7.20
C/N ratio	0.10	0.79	7.82
CO ₂ evolution rate	0.07	0.58	8.23

3.6.1 Normalized data

Normalised data of all attributes are shown below in Table 7. Temperature (temp) attribute was the main parameter of composting. Temp, being the beneficial attribute was the case of the maximization. All other attributes like pH, TOC, C/N, germination index, and CO₂ evolution rate increased or decreased due to variations in the temperature and thus were minimised. Also, rotary drums stayed in thermophilic phase for different number of days. R-2 drum was for 8 days in thermophilic phase. So, all temp values were divided by 8 so that normalised temp at R-2 will be 1 and its value in other drums will be <1 (refer normalized data and selection index, Table 7), respectively. Similarly, the minimum value of pH in R-3 was 7.230 and normalized as 1, and the other normalized value of pH was obtained by dividing 7.650 by each pH ($7.230/7240 = 0.999$).

Table 6: Attributes and alternatives for AHP method

Attributes ►							
Alternative▼	Temp	pH	EC	TOC	GI	C/N ratio	CO ₂ evolution rate
R-1	7.000	7.240	2.920	31.790	92.200	16.910	4.920
R-2	8.000	7.300	2.710	31.460	94.150	15.050	4.140
R-3	4.000	7.230	2.730	34.080	85.200	18.130	6.180
R-4	3.000	7.650	2.870	37.360	81.250	20.990	8.160

3.6.2. Selection index

Selection index is used to show the ranking of the drums. Higher the value of SI, better the alternative. It was obtained by multiplying normalized data by weight (MAT(A2)). The ranking of drums as per AHP method are as follows: R2> R1> R3> R4. Here, particle size 1.5-3.0 cm diameter showed optimum size for efficient composting of garden waste followed by 0.5-1.5 cm diameter.

Table 7: Normalised value and Selection index

Attributes ►									
Alternative▼	Temp	pH	EC	TOC	GI	C/N ratio	CO ₂ evolution rate	Mat (A2)	Rank
R-1	0.875	0.999	0.928	0.933	0.979	0.890	0.841	0.410	0.909
R-2	1.000	0.990	1.000	1.000	1.000	1.000	1.000	0.031	1.000
R-3	0.500	1.000	0.993	0.777	0.905	0.830	0.670	0.026	0.699
R-4	0.375	0.945	0.944	0.549	0.863	0.717	0.507	0.165	0.576
								0.197	
								0.1012	
								0.0702	

5. Conclusion

The present study was conducted to investigate the role of particle size on the degradation of garden waste using rotary drum composting method. The study was conducted with different particle sizes, 0.5–1.5, 1.5–3.0, 3.0–4.5, 4.5–7.5 cm diameter and 1.5–3.0 cm diameter gave optimum conditions for efficient composting of garden waste as per AHP method. The reduction in total volatile solids by 31.20%, CO₂ evolution rate of 4.1 mg/gVS/d, germination index of 94 % and C/N ratio of 15.05 within 45 days of composting is optimum conditions for rapid garden waste composting. An increase in particle size by more than 3.0 cm diameter is decreasing the performance of composting maturation. As per analytical hierarchy process

Declarations

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Figures

Figure 1

Pictorial and actual view of rotary drum composter

Figure 2

Temporal variations of (a) Temperature, (b) Moisture content, (c) pH, and (d) Electrical conductivity during garden waste composting

Figure 3

Temporal variations of (a) Total organic carbon (TOC), (b) Total volatile solids (TVS), (c) Ash content, (d) Ammoniacal nitrogen during garden waste composting

(a) CO₂ evolution rate

(b) C/N ratio

(c) Total Nitrogen

(d) Germination Index

Figure 4

Temporal variations of (a) CO₂ evolution rate, (b) C/N ratio, (c) Total nitrogen, (d) Germination index during garden waste composting

(a) Phosphorous

(b) Potassium

(c) C/P ratio

Figure 5

Temporal variations of (a) Phosphorous, (b) Potassium, (c) C/P ratio during garden waste composting

(a) Cellulose

(b) Hemicellulose

(c) Acid insoluble lignin

(d) Acid soluble lignin

Figure 6

Temporal variations of (a) Cellulose and (b) Hemicellulose (c) Acid insoluble lignin and (d) Acid soluble lignin during garden waste composting

Figure 7

Figure 7 shows the hierarchy structure for ranking of drums.

Supplementary Files

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