Optimization of Composting Parameters for the Production of Organic Fertilizers from Different Organic Waste Materials

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Abstract

Developing societies need to maximise the recycling of solid waste, and, to this end, compost production for improved soil fertility is a sustainable option for the waste recycling market.
With the objective of improving the quality of compost by the control of , the operating parameters in the composting process, a co-composting of different types of organic wastes, such as animal manures (from poultry, cow, horse), vegetables residues, plant residues and bulking agent (sawdust) was carried out.

Co-composting was executed at different C/N ratios ranging from 25 to 45 at moisture content of 55%. The windrow piles were mechanically turned using a special compost turner. Temperatures were rapidly increased from ambient temperature up to 60-70ºC during the first week. This range is enough for pathogen and weed seed termination. Mixtures of poultry and cow manures with 10% sawdust had more thermophilic temperature development than mixtures of street plant residue and manure. The windrows needed 10 weeks to complete the composting phases and produce stabilised products. The initial C/N ratios, which were ranged from 30 to 40, showed optimal composting processes and resulted in final products with relatively high maturation index (Mi), based on the proposed weighing factors. Furthermore, high C/N ratios of more than 40 resulted in low temperature development and slow degradation process, with relatively low Mi. The reduction of C/N ratio during the composting process is ranged from 38- 46%, and the highest C/N ratio reduction was achieved in the piles with high initial nitrogen content (low initial C/N ratio). Total pile volumes are decreased by 25-35%, indicating the levels of mass loss from composting. However, a 15% increase in the bulk density also occurred. A 1:1 ratio was assumed for the amounts of water (in volume) added in relation to the amounts of organic fertiliser (in volume) produced. Final product quality findings show that concentrations of all seven heavy metals (Pb, Zn, Cu, Cd, Cr, Hg and Ni) were significantly lower in all piles. On the other hand, compost respiration in the samples varied from 3.6 to 19.9 mgO_2/g dm. As a result, all the compost samples appeared to be stable and rated as class IV and V final products.

Keywords

Composting, Organic waste, C/N ratio, Heavy metals, Respiration activities, Maturation Index (MI).

Acknowledgements

The research experiments with annual capacity of 300 m^3 were conducted on an established composting pilot plant which is located at Al-Ghabawi landfill site around 40 km east of Amman, Jordan. The composting was carried out within the framework of the Jordanian government-funded Public Private Partnership (PPP) project for composting of organic wastes and production of organic fertilizers. This project was carried out over a six month period, from June2016. It was funded by the Greater Amman Municipality (GAM) and implemented by its Jordanian private partner (Mustafa Al Jaar Establishment for Consultation), which closely cooperates with the University of Rostock in Germany as well as the National Centre for Agricultural Research and Extension (NCARE), Jordan.

1. Introduction

Every year, worldwide, millions of tons of solid wastes are generated from agricultural, municipal and industrial sources. These amounts are expected to increase exponentially due to predicted population growth and increased urbanisation.

One solid waste material, agricultural waste, includes large quantities of animal manure. The quantity of animal manure produced in each country is estimated to be 110 times that of human waste [1].

Economic growth and increase in consumption have led to intensification of animal husbandry [2]. More intensive animal farming (cattle, sheep, goats and poultry), to meet escalating demand for animal products (milk, meat and egg), has led to an increase in production of livestock manure.

Generally, livestock manure is defined as, "livestock excreta, unconsumed feed and associate bedding material". This manure is a valuable by-product of the livestock industry and traditionally used as a fertilizer to improve land productivity. Most farms, however, do not own enough land to use animal manure as fertilisers. The staggering amounts of unmanaged livestock manure create a real problem for human health and the environment. The uncontrolled decomposition of the organic solid waste can produce large-scale contamination of the ecosystem (soil, water, and air) [3].

Organic components of the solid waste can be converted into a valuable source of energy by anaerobic digestion (AD) or composting. Composting is a technique which can be used to reduce the amount of organic waste through recycling and the production of soil fertilisers and conditioners. Compost is primarily used as a soil conditioner rather than a fertiliser because it contains a high organic content (90-95%) but generally low concentrations of nitrogen, phosphorus, potassium, as well as macro and micro nutrients, compared to commercial fertilisers. It is comparable to peat moss in its conditioning abilities. Consequently, compost maturity is the most essential criterion in recycling animal manure, as well as in relation to its marketing and utilisation in agriculture as organic amendments. Composting can be beneficial in the recycling of the organic fraction of the solid waste, reducing as much as 30% of the volume of organic matter entering our already overcrowded landfill sites. Furthermore the composting process, if performed correctly, transforms wet and odorous organic waste into an aesthetically dryer, decomposed and reusable product [1].

On the basis of the elementary value of organic compost in its ability to store water, an essential component for plant growth and soil support, and to eliminate environmental problems resulting from manure use in agriculture, composting is considered to be a convenient method to assist farmers in the conservation of their natural environment.

Composting is a viable option for manure management, and may be carried out in a variety of ways, ranging from simple, low cost, passive piles to sophisticated, and automatically controlled in-vessel systems. Regardless of the system used, if it is managed properly, aerobic thermophilic composting will reduce the amount of material to be handled and, thereby, reduce transportation and spreading costs, as well as controlling pathogens, weed seeds and odours.

Composting can be commonly carried out in two ways: aerobic composting (with oxygen), and anaerobic composting or fermentation [4]. Aerobic composting is the simplest and more economic choice, being more adaptable to local conditions and capacities. In addition, it is a very rapid process and relatively efficient in terms of time, equipment and labour.

In most countries, the animal industry faces the challenge of how to reduce the hazards of increasing production of livestock manure, as well as optimising benefits derived from this inevitable by-product. This challenge requires careful planning for sustainable, viable and economic utilisation of animal manure, in an environmentally and socially acceptable manner [5].

Jordan is among the developing countries that depend greatly on agriculture and livestock farming, which produces high amounts of organic fresh manure annually [6]. Enhancement of soil quality and crop yield is offered by the potential for compost application [7].

The current practice of producing organic fertilisers by means of composting, either in-situ (by farmers) or ex-situ (by manufacturers), neither follows state-of-art techniques nor does it comply with national and international standards. In addition, there are no monitoring programs or quality assurance strategies for Jordanian compost producers in place. Therefore, the introduction of an innovative and engineering-based technology is highly imperative [6].

Improperly stored or applied livestock manure can pollute water resources (surface and underground water) and diminish air quality. The seepage of manure contaminants (phosphorous, nitrates, heavy metals, and pathogens) can infiltrate drinking water sources. Gases emitted from the decomposition of manure can pollute the air, increasing vulnerability to respiratory diseases. Manure stockpiles provide a favourable environment for proliferation of insects and rodents, and this can result in transmission of diseases to humans and animals.

In Jordan it is estimated that manure production from dairy cattle and poultry (chickens) was approximately 0.49 million dry tons in 2012, increasing to 0.52 million dry tons when combined with bedding material. Of the 0.52 million dry tons produced, approximately 0.45 million tons could be considered collectable for beneficial use or disposal. These generated amounts increase annually, although capacity to handle these materials has declined. Recently, there is an increased interest in

Jordanian society in local handling and use of organic residuals for use in soil conditioning and plant support [4].

Many existing local laws and regulations influence manure transfer, collection, and composting enterprises from site selection, specifications and standards of compost, to product marketing. In most cases, these laws are not actually enforced, and most of them need reviewing and modification in order to be more suitable and realistic for all stakeholders and partners concerned.

Changing public perceptions about environmental issues associated with current manure management practices have forced farmers to examine alternative options [8, 9]. The composting process offers the potential to significantly reduce environmental problems associated with manure management [10]. There is an increase in agricultural utilisation of compost, and many countries are developing procurement programs for compost use on highways and for erosion control [11].

It is important to address manure treatment to reduce pathogens, volume and odour, before land application. Livestock producers constantly face the challenge of managing manure and meeting environmental regulations.

The lack of an enabling environment is to blame for such market failure. In Jordan, there is no policy for organic animal waste management, so current practices for managing this waste are based on existing environmental regulations and legislation. There is a shortage of specialised facilities equipped with the state-of-the-art technologies required to process this waste in a sound and scientific manner, with the capacity to produce manure of a suitable quality for local cultivation, and with production capabilities that meet the needs of the local market, There is also a lack of skilled knowledge, experience and training in the fields of composting processes.

The application of a state-of-the-art windrow composting method in this research will ensure the production of environmentally safe organic fertilisers, which will definitely reduce the demand for chemical fertilisers and eliminate the negative impact from the application of untreated animal manure in agriculture.

Organic materials have diverse bio-chemical characteristics, so their treatment methods vary accordingly. However any treatment process would require a comprehensive overview of the main parameters affected by the treatment process. It was the main goal of this research to control and optimise the operating parameters in an aerobic composting process using windrow technique for different types of organic wastes produced locally as livestock manures, vegetables residues and plant residues, in order to determine the best composting conditions. On the one hand, the strategy consisted of improving different organic waste processing (composting parameter process) techniques. On the other hand, it required the determination of the optimum mixing ratio of animal manure (poultry, cow, and horse), vegetables residues and plant residues, in relation to bulking agents (sawdust), to ensure the production of high grade compost under ideal conditions, and to comply with national and/or international standards. A further objective was to highlight the efficiency of this approach as one of the most significant recycling options, in order to draw the attention of decision-makers to its importance and the necessity to find laws and regulations governing the establishment of such projects, and thus to circulate the concept to the rest of Jordan.

2. Study Area and Livestock Manure production

The pilot composting project was conducted on an established composting pilot plant which is located at Al-Ghabawi landfill site around 40 km east of Amman, Jordan.

Historically, manure has been a primary source for plant nutrition. Its value for maintaining and improving the productivity of the soil has been recognised from the earliest times.

The decomposition of organic matter in the soil slowly releases nutrients such as nitrogen, phosphorus and potassium, and thus improves soil nutrient retention and reduces nutrient leaching [12]. The addition of organic matter to soil has been shown to improve water holding capacity, Cation Exchange Capacity (CEC), aggregation and bulk density, buffer pH changes, and increase microbial diversity and activity [13].

Pollution by livestock wastes has become a significant concern in many countries. However, there is an increased interest in Jordanian society for local handling and use of organic livestock residues for use in soil conditioning and plant support [6].

Jordan is considered to be an agricultural economy based on agriculture and livestock farming. Approximately 3,250 regular farms now raise livestock, according to recent statistical survey reports compiled by the Jordanian Department for Statistics (JDS) and Ministry of Agriculture (MOA) in 2006.

In Jordan, many studies have reported data about animal manure production. Abu-Ashour (2010) stated in his study that 72,000 head of dairy cattle and 40 million hens generated about 5.3 million tons of solid waste (as excreted) per year, with 200,000 tons of the total amount of BOD from animal waste per year [14]. Assam et al. (2010) estimated the annual production of wet manure from dairy cattle and poultry facilities to be 980,775 tons [15]: these estimates were based on dairy cattle population of 96,917 head compared to 66,000 head of dairy animals, as reported by MoA (2012) [16]. As a result, the reported values of wet manure production were overestimated. Another study by Abu Hamatteh et al. (2010) indicated that animal manure generated in Jordan, according to the study conducted by the Greater Amman Municipality in 2009, was comprised of 800,000 tons of cattle manure and 350,000 tons of chicken litter: a total of 1.15 million tons [17].

The local livestock sector generates approximately one million cubic metres of fresh manure, which consists mainly of chicken and cow manures, as shown in Table 1. According to these statistics, the largest amount of manure is produced by poultry, followed by cattle, breeders and horses. The high amount of poultry manure is mainly due to the number of poultry farms, which are widespread in agricultural and desert areas across a radius of 100 km around Amman city. These farms vary in size, from small to very large, as was found to also be the case for the cattle farms.

Until now, no standards for manure treatment or composting processes have been made applicable to manure producers. Locally generated manure is usually disposed of by direct application into agricultural fields. Jordan faces many environmental challenges, such as water scarcity, land desertification and aridity, soil salinity and frailty. The local agricultural sector consumes around 65 percent of the available water resources [18] and high amounts of chemical fertilisers of different types [6]. Therefore, the agricultural sector has to be developed in order to face increasing demands and to achieve agricultural self-sufficiency.

Table 1. Livestock manure production in Jordan (Source: JDS and MOA, 2006)

Livestock	Regular farms	Manure production m^3/yr	%
Poultry (Broilers and Layers)	2455	580,000	54
Breeders	100	65,000	6
Cow	678	370,000	35
Horse	7	55,000	5
Sheep and Goat	N/A	N/A	N/A
Total	3240	1,070,000	

An increase in agricultural production requires the use of organic materials in order to improve soil properties, provide the plants with nutrients needed for growth, aerate the soil, and improve its water holding capacity [19]. Animal manures can be used as natural fertilisers based on organic origin, but they should be pre-treated before application, in order to avoid potential negative impacts.

Agriculture in Jordan, particularly the Jordan Valley, includes mainly vegetables, fruit trees, and the field crops. Table 2 shows the types of agricultural areas, with the average potential amount of organic fertilisers needed. Currently, there is a high market potential for organic manure materials that can be used in the various agricultural production activities in Jordan. Consequently, recent local demand is satisfied by using the fresh manure residues which have been produced in livestock farms, combined with further chemical fertilisers, as required.

Aerobic composting is becoming an environmental alternative method for treating locally generated manure wastes and supplying the local market with natural organic fertilisers that are used in agriculture [20]. Organic matter content in compost ranges from 30-50% of dry weight, with the remainder being minerals [21].

The application of compost to agricultural land as a fertiliser builds the physical structure and enhances CEC of soil, increasing its ability to retain water and to avoid leaching nutrients. In addition, compost amended soil has been found to act as a suppressant against plant diseases caused by nematodes, bacteria, or soil-borne fungi in various cropping systems [22].

Table 2. Agricultural area and manure market potential in Jordan [6]

Type of plant	Area (dunams)	Amount of Manure Required m^3/dun.	Market Potential m^3
Open field vegetables	453,743	3	1,361,229
Greenhouse vegetables	11,075	4	44,300
Potatoes and watermelons	68,950	3	206,850
Orchards	976,468	1.5	1,464,702
Nurseries	N/A	60 - 150 m^3/ Nursery.	30,000
Total	1,519,236		3,107,081

Inorganic fertilisers have higher macronutrient content per volume, but do not improve the physical structure of the soil. Accordingly, use of manure-based compost instead of fresh manure in agriculture practices is considered as an environmental and economic solution for manure waste management, by changing from simple disposal to the production of a value-added, high nutrient product. Table 3 shows the comparison among composted and uncomposted manure.

Table 3. Advantages and disadvantages of composted and uncomposted manure [23]

Compost	Manure
Slow-release nutrients	Usually higher nutrient content
Easier to spread	Sometimes difficult to spread
Lower potential to degrade water quality	Higher potential to degrade water quality
Likely to contain fewer weed seeds	Likely to contain more weed seeds
Higher investment of time or money	Lower investment of time or money
Reduced pathogen levels (e.g. salmonella, E. coli)	Potential for higher pathogen levels
No fly or other vectors in the stable compost	Breeding of fly and other vectors
More expensive to purchase	Less expensive to purchase
Reduced odors (although poor composting can create foul odours)	Odours present a problem

3. Materials and methods

3.1 Background

This research was conducted to optimise the operating parameters in an aerobic composting process using windrow technique for different types of organic wastes which are locally produced as livestock manures, vegetables residues and plant residues. Aerobic composting is currently considered to be a convenient way to improve manure's current status and help farmers to conserve their natural environment. Temperature, moisture content, C/N ratio, turning frequency, and oxygen percentage in air pores inside piles are generally the main factors affecting aerobic composting. Composting duration was between 15 and 180 days, as reported by Michel et al., (1996), for converting manure into stabilised compost [24]. The efficiency of using compost in agriculture is dependent on the characteristics and practices applied in manure processing [25]. Figure 1 shows the flow chart of the general methodology of aerobic windrow composting which is followed in this research.

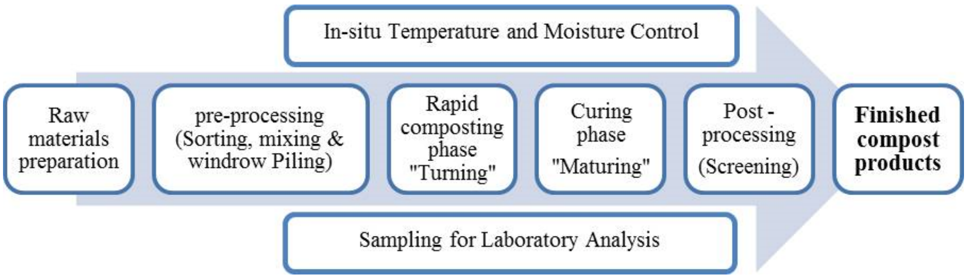

Fig. 1. General research methodology flow chart

Several key process management parameters are commonly used to monitor and control the composting progress. Figure 2 provides a summary of the different control parameters to define optimal composting conditions and the product quality assurance. These parameters apply to all composting methods and technologies. However, the emphasis placed on each parameter varies from facility to facility, depending upon feedstock types, composting technology, and operator experience.

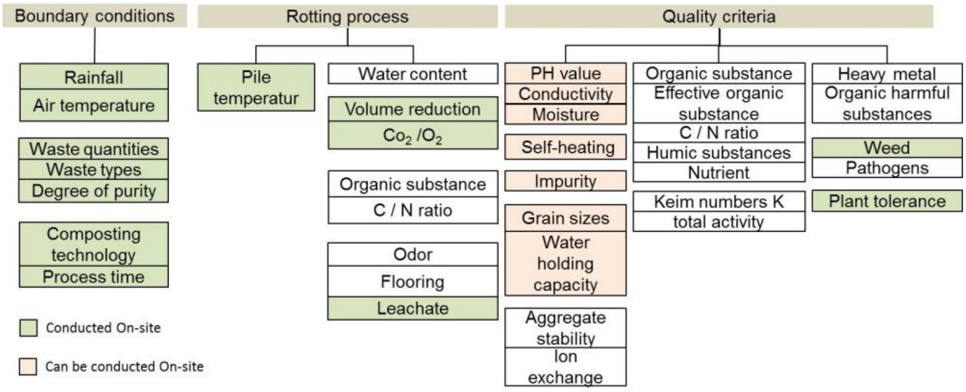

Fig. 2. Control and quality assurance parameter for composting and final product

Different composting runs have been carried out to achieve specific goals of the research project. At each run, many different organic raw materials (cows, poultry, and horse manure) are blended with each other in certain ratios and gently mixed with vegetable residues and bulking agents (sawdust or tree leaves); then suitable conditions to support rapid aerobic composting (moisture and aeration) are supplied directly after mixing.

The mixed materials are aligned in long windrow piles by end-front loader and turned mechanically, using a specialised windrow turner, to rapidly start composting, and needed 70 days to produce finished compost products. Differences in the input materials influence the final C/N ratio of the pile. The composting process is frequently monitored by typical operating parameters, such as temperature, oxygen, pH, moisture content and C/N ratio.

3.2 Experimental site

The research experiments, with annual capacity of 300 m^3, were conducted on an established composting pilot plant located at Al-Ghabawi landfill site around 40 km east of Amman (see Figure 3). The composting was carried out within the framework of a Jordanian government Funded Public Private Partnership (PPP) project for composting of organic wastes and production of organic fertilisers. This project was started in June 2016 and continued for six months. It is funded by the Greater Amman Municipality (GAM) and implemented by its Jordanian private partner (Al Jaar Consultants Company), which closely cooperates with the University of Rostock in Germany, and also with National Centre for Agricultural Research and Extension (NCARE), Jordan.

Fig. 3. Location of the composting experimental site (Al Ghabawi landfill)

3.3 Raw materials and pile construction

On the basis of the elementary value of compost as a natural fertiliser in agriculture, as figure 4 shows, different types of organic wastes as animal manures (poultry, cow, and horse) have been used as composting input material. Plant residues, vegetables residues and sawdust have been used as bulking agents to ensure the required C/N ratio needed for efficient decomposition. Furthermore, poultry manure, the most easily available manure in Jordan, serves as one of the most important input materials in the composting process.

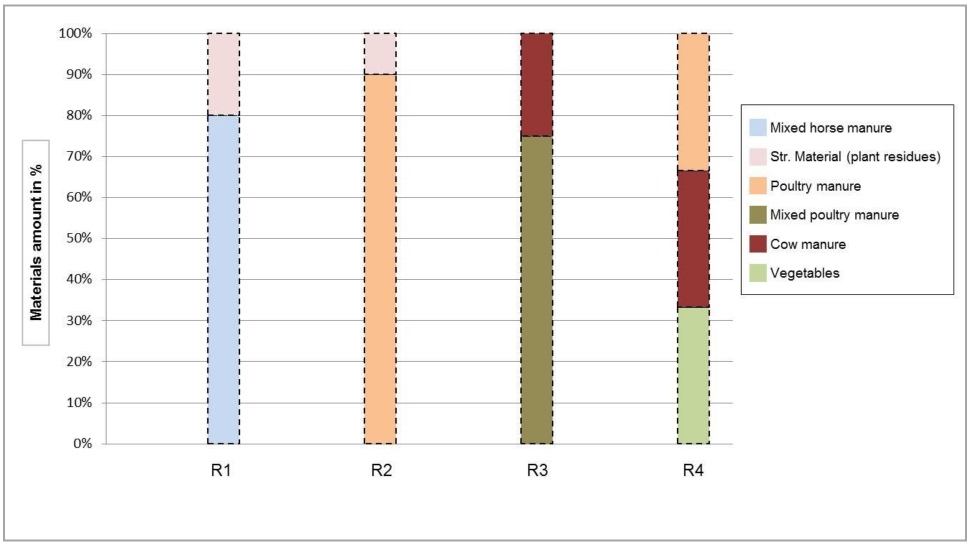

Fig. 4. Materials types and ratios used in each run.

Four compost runs consisted of three mixtures R1, R2, R3 and R4. Each run was constructed with different proportional amounts of raw materials, C/N ratios and over different time periods (see Table 4).

Table 4. Compost runs ingredients and composting time

Compost Run 1	**Experiment Date: 28.08 - 06.11.016**	**C/N_M***	**Run No.**
Pile 1	75 % Mixed horse manure** + 20 % Str. Material Plant residues	31	R1
Compost Run 2	**Experiment Date: 17.09 - 26.11.016**		
Pile 1	90 % Poultry manure + 10 % Str. Material (plant residues)	28	R2
Compost Run 3	**Experiment Date: 25.09 - 04.12.016**		
Pile 1	75 % Mixed poultry manure + 25 % Cow manure	33	R3
Compost Run 4	**Experiment Date: 04.10 - 13.12.016**		
Pile 1	33.5% Vegetables + 33.5 Cow+ 33% Poultry	41	R4

Note:
*** C/N_M is a theoretically calculated ratio for the resulting mixture.**
**** Mixed manure means that it is mixed with 10 percent sawdust (v/v).**

All materials used in the composting processes were analysed for different parameters using International Centre of Agricultural Research in Dry Areas (ICARDA) methods for nutrient extraction procedures [26] and international standard methods for examination of water and wastewater [27], at the NCARE laboratories and University of Rostock laboratories, Germany. Table 5 summarises the analysed parameters, with their corresponding standard methods.

Table 5. Laboratory measurement of composting parameters with their corresponding standard methods

Parameter	Method	Reference
Moisture Content (MC)	Using electronic oven by drying at (105 C^o for 24 hr) (w/w).	[26]
EC	(1:10 w/v sample: water extract) by an EC meter with a glass electrode.	[27]
Ash Content	Muffle furnace by Ignition at (550 C^o for 6 hr).	[27]
Total Organic Carbon (TOC)	TOC (%) = ((100 - Ash %) ÷1/8)	[28]
C/N Ratio	Expressed as ratio of (TOC / TKN) %	
Total kjeldahl-N (TKN)	Regular-kjeldahl Method (automatic analyser)	[27]
Total P and K	Atomic absorption spectrometric methods	[26]
Respiration Activities (AT4)	Soil quality-Laboratory methods for determination of microbial soil respiration (ISO 16072:2002)	[29]
Heavy Metals	Inductively Coupled Plasma-Mass Spectrometer, Thermo-Elemental ICP-MS-X Series	[30]

The characteristics of initial raw materials used in composting experiments are presented in Table 6. After raw materials are prepared for composting, they should be sorted, screened and shredded if found to contain large pieces, and then mixed in certain ratios to maintain nutrient content and bulk porosity.

Table 6. The characteristics of initial raw materials used in composting

Raw Material Type	Animal Manure			Bulking Agents	
	Mixed Poultry	**Cow**	**Horse**	**Sawdust**	**vegetables**
Parameter					
Bulk density Kg/m^3	392.00	612.00	764.00	278.00	820.00
Moisture Content MC (%)	31.10	21.00	37.00	8.00	72.00
Dry Organic Matter (%)	66.80	77.50	82.10	91.00	60.00
Total organic Carbon (%)	37.00	43.00	45.50	50.50	38.10
Total Nitrogen (%)	2.81	2.14	1.81	0.13	1.20
C:N Ratio (w/w)	13.00	20.00	25.20	400.00	25.00
pH	8.06	8.69	9.14	5.90	6.50
EC (dS/cm)	3.67	3.17	3.74	0.42	3.60
Total P (%)	2.47	1.94	0.93	0.03	0.62
Total K (%)	1.42	2.07	1.01	0.01	0.53

The method of composting based on principle of windrow technology is carried out by means of turning that allows the aerobic decomposition of organic waste into odour free and stable compost. Therefore, the prepared materials are well-blended and aligned in long windrows piles, in dimensions of 60m long, 2m width and 1m height, to ensure efficient mechanical turning. Most manures are a good source of nitrogen but may be low in carbon, depending on the amount of bedding used. Most materials available for composting do not fit the ideal ratio, so different materials must be blended. Proper blending of carbon and nitrogen helps ensure that composting temperatures will be high enough for the process to work efficiently and ensures adequate supplies of other nutrients are available for microbes.

During the four composting runs, four windrow piles from different organic wastes were aerobically composted using windrow system in an open site area. Each compost run consisted of one pile. The raw materials were mixed of different component ratios (weight basis) depending on theoretical calculations to adjust initial C/N ratios between 20 and 40, as recommended for rapid aerobic composting.

The initial C/N ratios are theoretically calculated according to the following formula [31]:

$$\mathbf{C/N_M} = \frac{\Sigma\,(C/N_{1...n} \times t_{1...n})}{\Sigma\, t_{1...n}}$$

where,

C/N_M : C/N ratio of resulting mixture.

$C/N_{1...n}$: C/N ratio of individual components of the mixture, (from 1 to n).

$t_{1...n}$: mass of individual components of the mixture in tons, (from 1 to n).

3.4 Composting process

The composting system is adopted in this pilot plant based on principles of windrow technology. The composting piles were turned mechanically using special compost turner (BACHUS 14.28 Turning machine, China), and according to a turning schedule as follows: 1) 3-4 turnings in 1st week, 2) 2-3 turnings in 2nd week, 3) 2 turnings in 3rd week, 4) one turning per week in the 4th and 5th weeks, and, from the 6th week onwards, one turning every 2 weeks if heating still occurs.

Water was continuously added to the piles to achieve the required moisture content of 50 – 60% (wet basis). Temperature is expected to increase due to the microbial activity and should be noticeable within a few hours of forming a pile, as easily degradable compounds will be consumed. Temperature can be measured with a digital probe of one metre (three feet) long.

It is expected, that the composting process will finish 8 weeks from the first turning. However, the compost remained in the pile for 2 additional weeks for the purpose of curing, so that each pile requires a total of 10 weeks to accomplish complete composting. However, to eliminate the prolongation of the research project time, the four runs were been carried out at convergent time intervals.

3.5 Sampling and Analytical Procedure

During the implementation of composting runs, a continual monitoring program was carried out on daily basis and permanent control of the pile was maintained. This program contained direct in-situ measurement for operating parameters of composting process as temperature, pH, oxygen and carbon dioxide percentage (v/v) inside windrow piles. These parameters helped to schedule the turning frequency of the piles.

For data interpretation during composting process, a regular sampling was carried out during the different stages of composting. In-situ measurements which complied with the parameters to ensure proper composting process and to indicate the composting maturity are tabulated in Table 7. The table also shows the frequency of parameter analysis. The ambient temperature and temperature within each pile were measured daily. The pile's temperature was measured by dividing the pile into five equal sections and taking temperature readings at five locations for each section (at pile bottom, 0.25cm from the bottom, in the middle, 0.25cm from the top, and at pile surface), then the average readings were taken.

CO_2 and O_2 percentage inside each pile were measured directly using digital meters (Models 115 and117 Testoryt Compost Systems) and before turning operation (twice reading per each pile). The pH values were measured using pH meter with glass electrode (1:10 w/v compost: water extract).

Table 7. In-situ measurements of operating parameters during composting process

Test	Method	Frequency
Temperature	using a digital dry bulb thermometer (Compost Systems)	daily
O_2 (v/v)	using Oxygen meter (Testoryt O_2 Compost Systems, Model 117)	once a week
CO_2 (v/v)	using Carbon Dioxide meter (Testoryt CO_2 Compost Systems, Model 115)	once a week
pH	(1:10 w/v sample: water extract) by a pH meter (GPRT 1400) with a glass electrode Redox-Electrode GE 105	once a week

Representative samples were collected by dividing the pile into five equal sections and taking samples at three locations in a pile (0.25cm from bottom, in the middle, and 0.25cm from the top). The collected samples were analysed at NCARE laboratories for the following parameters: moisture content (oven drying 105^{o}C for 24hr), ash content (expressed as percentage of residues after muffle furnace ignition at 550^{o}C for 6hr), and Total Kjeldahl Nitrogen (TKN) using regular kjeldahl method by FOSS Kjeltec™ 2300 Analyser Unit. Due to the lack of potential at NCARE labs to analyse the stability analysis (AT4) and heavy metal concentrations of the samples, the collected samples were sent to Rostock University laboratories, Germany, for analysis. The frequency of the parameters analysis is listed in Table 8.

Table 8. Frequency of composting parameters analysis in the laboratory

Laboratory Test	**Frequency**
Moisture Content (MC)	every two weeks
EC	every two weeks
Ash Content	every two weeks
Total Organic Carbon (TOC)	every two weeks
C/N Ratio	every two weeks
Total kjeldahl Nitrogen (TKN)	every two weeks
Total P and K	start and end
Total organic matter	at the end
AT4	at the end
Heavy Metals	at the end

The total organic carbon was estimated from ash content according to the formula of [28] as:

$$\mathbf{TOC\ (\%)} = \frac{\mathbf{VS\ (\%)}}{\mathbf{1.8}} = \frac{\mathbf{100 - Ash(\%)}}{\mathbf{1.8}}$$

where,

TOC (%): percentage of total organic carbon.

VS (%): percentage of volatile solids.

Ash (%): percentage of ash content.

The C/N ratio was calculated using the following formula:

$$\frac{\mathbf{C}}{\mathbf{N}} = \frac{\mathbf{Carbon\ Content\ \%}}{\mathbf{Nitrogen\ Content\ \%}} = \frac{\mathbf{TOC\ (\%)}}{\mathbf{TKN\ (\%)}}$$

The total P was measured colorimetrically [32], and total K by flame photometry [27]. For the purpose of evaluating the stability of the compost final product and determining the optimum C/N ratio, a composting maturation index (Mi) was calculated according to formula [33]. Mi was formulated depending on maximum achieved temperature, active composting time, percent range reduction in C/N ratio, and other parameters, as shown in the following equation:

$$\mathbf{M_i} = \mathbf{a}\frac{\mathbf{T_{max} - T_{amb}}}{\mathbf{T_{max}}} + \mathbf{b}\frac{\mathbf{T_{HCP}}}{\mathbf{t_T}} + \mathbf{c}\frac{\mathbf{T_{LCP}}}{\mathbf{t_T}} + \mathbf{d}\frac{\mathbf{\Delta_{CN}}}{\mathbf{F_{CN}}}$$

where,

a, b, c, d : weighing factors

Tamb : average ambient temperature, °C.

Tmax : maximum achieved temperature, °C.

THCP : time at which the temperature remains above the highest control set point (60 °C), day.

TLCP : time to reach the lowest control set point (40 °C), day.

tT : total composting time, day.

ΔCN : arithmetic difference between initial and final C/N ratios.

FCN : final C/N ratio.

High value of Mi indicates high potential efficiency of composting process due to high temperature generation, lingering thermophilic condition, prolonged composting, and high C/N reduction.

4. Results and discussion

This section discussed the main operating parameters in aerobic composting experiments in an open site under ambient conditions. The experiments were carried out entirely according to the methodology discussed earlier. The effects of operating parameters on active composting are intensively discussed.

4.1 Characteristics of raw materials

It is widely known, that three components are required for building a compost mixture, including the primary substrate, amendment, and bulking agents [34]. In this research, poultry, cow and horse manure, and vegetables are considered as the primary substrate. Sawdust is mainly considered as an amendment to balance C/N ratio or modify the pH value. Plant residues or branches and woodchips have been used as bulking agents to provide structure and porosity for compost piles. Locally, poultry manure is the most common by-product of the livestock sector and the amounts generated increase annually. Fresh poultry manure produced from commercial poultry farms is usually mixed with approximately 10% sawdust, which is used as bedding layer in these farms. In other livestock production, such as cow and horse farming, large amounts of organic manures are produced as by-products and are generally disposed of by being given to local farmers for land application. The fresh mixed poultry manure, with 10% sawdust, is the main input for compost mixtures with C/N ratio of 13 and moisture content around 30 percent. The C/N ratios of fresh cow manure, horse manure, vegetable waste, and sawdust are 20, 25, 58, and 400 respectively.

The mixing ratios have been theoretically calculated based on Amlinger, et al., (2005) formula, to achieve a C/N ratio that ranges from 20 to 40 for mixtures depending on weight basis [31]. The moisture content for prepared piles is adjusted to range from 50-60% (w/w). The blended ratios for compost mixtures are listed in Table 4, and the physical and chemical characteristics of raw materials are listed in Table 6. The composting process has been carried out at ambient conditions in an open site and needed 10 weeks to achieve biologically stabilised and heat sterilised compost.

4.2 Compost runs results

This section showed the experimental data which are collected during composting experiments. All tables and figures in this chapter were constructed from these results. The experiments were carried out during four runs which contained four compost mixtures. The parameters; temperature, moisture content, pH, oxygen, carbon dioxide, C/N ratio, volume reduction, bulk density, nutrient content, and water consumption were controlled and monitored during composting. AT4 analysis and heavy metals concentrations were analysed at Rostock University laboratories, Germany.

As previously mentioned, the four compost runs consisted of three mixtures, R1, R2, R3 and R4. R1 was formed from four portions of horse manure and one portion of plant residues (4H: 1plant residues), R2 from nine portion of poultry manure and one portion of plant residues (9P: 1Plant residues), R3 from three portion of poultry manure and one portion of cow manure (3P: 1C), R4 from one portion of vegetable waste, one portion of cow manure and one portion of poultry manure (1V: 1C: 1P).

Water was added to provide optimum moisture which is critical to microorganism function during the composting process. After that, windrow piles were mechanically turned, according to periodic schedule, to maintain effective aerobic decomposition. Monitoring of temperature, moisture content, and oxygen supply was carried out to ensure an effective composting process. The initial physical and chemical characteristics of composting piles during the four runs are listed in Table 9.

Table 9. The initial physical and chemical characteristics of composting runs

Parameter	R1	R2	R3	R4
Ash Content (%)	57.2	55.7	56.5	57.2
Volatile Solids (%)	43.9	43.5	43.5	42.8
TOC (%)	24.4	24.2	24.2	23.8
TKN (%)	1.06	0.78	0.70	0.61
C/N Ratio (w/w)	28.0	31.0	36.0	41.0
Moisture Content MC (%)	25.0	23.0	31.0	44.0
pH	6.91	7.14	7.36	7.96
EC (dS/m)	2.43	2.39	2.01	3.59
Total P (%)	1.02	1.41	1.21	1.15
Total K (%)	1.28	1.32	1.39	1.17
Initial Pile Volume m^3	37.0	48.0	42.0	40.0
Initial Bulk Density Kg/m^3	453.0	417.0	406.0	587.0

The windrow piles needed 10 weeks to convert into stable and homogenous compost products and to complete the two composting phases. The main operating parameters which are controlled and monitored directly during composting are discussed in the following sections.

4.3 Temperature

As previously discussed, temperature is considered as a major parameter that was continually monitored on-site. An increase in the temperature was clearly observed during the early phase of composting for all piles. The results of average temperature profiles are shown in Figure 5. According to this figure, all piles demonstrated a typical composting temperature trend, achieving thermophilic temperatures of more than 55°C, and reaching approximately 67°C within two weeks, especially in piles R3 and R4 (thermophilic phase). Thereafter, the temperature declined slightly to around 60°C, and remained above 50°C from week 4 to week 6, before dropping further.

However, R1 and R2 showed some retardation in the biological processes, probably due to the low C/N ratio (high nitrogen content) which inhabits the carbonaceous degradation of raw compost material [25, 35]. The temperatures in all piles were found to be more than 50°C for the first 6 weeks of composting (active phase). The second phase of composting (curing phase) showed a faster rate of temperature decrease.

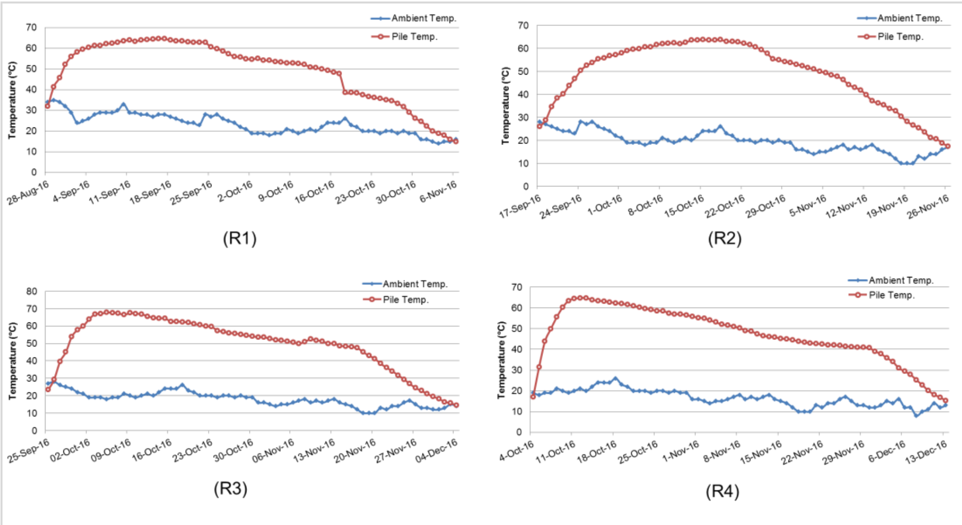

Fig. 5. Average temperature profiles during composting runs.

As the process was progressing, temperature started to decrease gradually after five weeks and, with ambient temperature, reached a constant level after 10 weeks. Relatively, during this run, and especially in R4, the short thermophilic development and continual temperature decrease indicated high initial C/N ratios and carbon content within raw materials used in composting.

In windrow composting, windrow size, turning frequency, initial C/N ratio, ambient temperature, moisture content, and oxygen supply are among the variables that affect temperature [36]. The thermophilic period for all piles was achieved according to USEPA guidelines for pathogen control during active process [37].

As organic matter became more stabilised, the microbial activities and decomposition rate declined, and thus the temperature gradually decreased to ambient level, marking the end of the active phase. The reduction of pile temperature to ambient temperature was clearly evident in the last four weeks, indicating that maturation process of organic materials into biologically stabilised products was efficiently accomplished.

4.4 Moisture content

Moisture content was monitored to maintain adequate water content, in order to ensure proper aeration and, thus, aerobic degradation and composting throughout the entire experimentation. In general, moisture content decreased gradually during composting, causing slow decomposition and low temperatures. In order to maintain optimum microbial activity with enough oxygen supply, water was added to maintain moisture levels at around 50%. Figure 6 shows the variations of moisture content during composting runs.

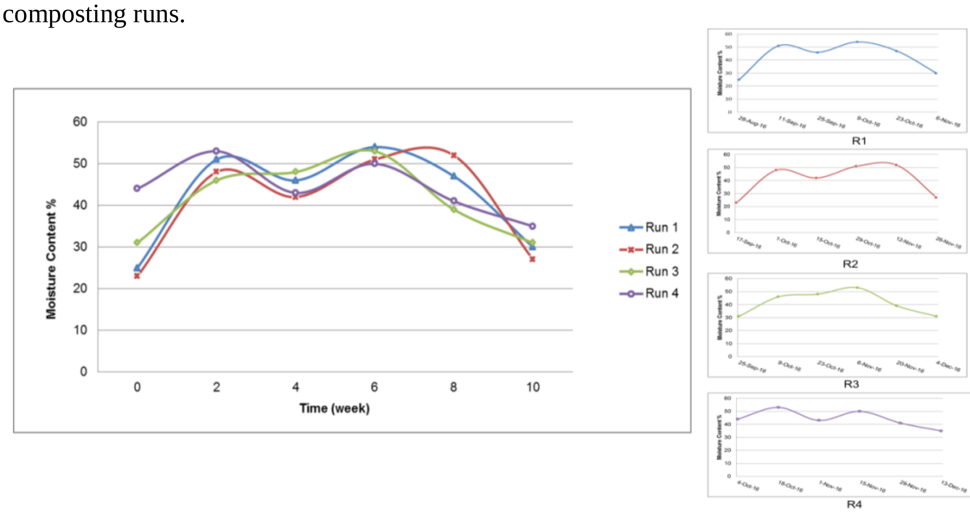

Fig. 6. Average moisture content during composting runs

High variations in moisture content during the active composting phase, especially between week 2 and week 6, are attributed to thermophilic temperatures, due to vigorous microbial activity, as well as the excessive turning frequency which reduced the existing moisture content inside the piles in relative amounts. As the curing phase started at the end of week 6, the moisture content in all entire piles gradually decreased to around 30%, especially in R2. The high water content in the pile R4, at the beginning of composting, is attributed to the lower pile temperature in comparison to the other piles [38]. The final moisture content in the pile R4 products was 37%, attributed to high initial C/N ratios which reduce the decomposition rate.

4.5 C/N ratio

In addition to temperature and moisture content, C/N ratio is one of the most important parameters in the composting process, and should be monitored continually. The C/N ratio plays an important role in the nutrient balance in a composting mixture, indicating the amount of carbon available, in relation to nitrogen, for the composting microorganisms.

The results of C/N ratios obtained during composting at different time intervals are shown in Figure 7. As seen in the graph, the four piles have different starting C/N ratios. It can be clearly observed that the initial C/N ratios are in the range of 25 to 45 in the all piles. However, they all showed similar C/N ratio reduction profile and trend. The rate of C/N ratio clearly decreased in the second phase of composting (after 6 weeks), in comparison to the first phase (up to 6 weeks) of composting. This, however, is expected as a result of the lower degradation rate in the second phase.

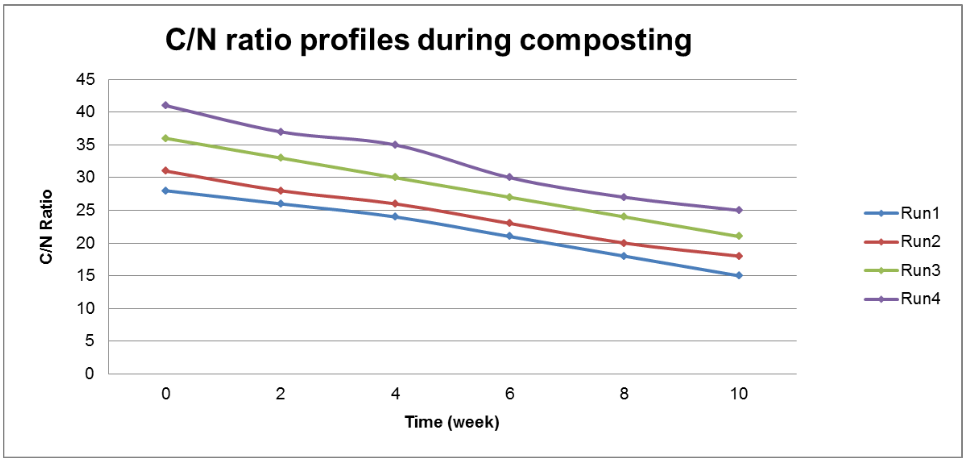

Fig.7. Average C/N ratio profiles during composting runs

The reduction of C/N ratio for all piles is presented in Figure 8. It is clearly seen that the highest reduction of C/N ratio took place in the R1 pile, where a more than 45% reduction was achieved. This high reduction can be attributed to the degradation process, as well as to the low starting C/N ratio [25]. Accordingly, in spite of the high starting C/N ratio, pile R4 exhibited a C/N ratio reduction of about 38 %. The total C/N ratio reduction in R2 and R3 was 41 and 42% respectively.

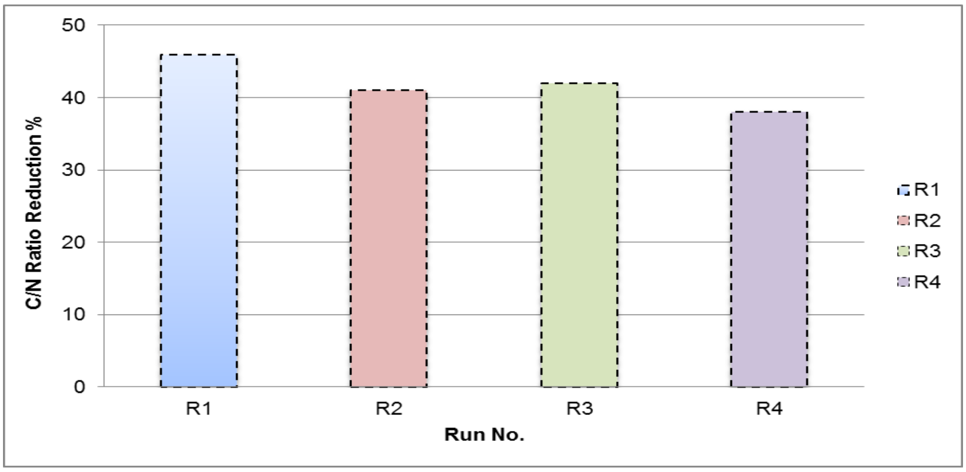

Fig. 8. C/N ratio reduction profiles during composting runs

As decomposition proceeded, the nitrogen content of the piles generally increased. In a dried compost sample from R1, the nitrogen content of the total compost material increased from 1.06% in week 0, to 2.98% in the last week of composting. Accordingly, carbon ash content was slightly decreased due to high microbial activity during composting, where large amounts of carbon were transformed via microbial respiration to CO_2 [39].

4.6 Turning frequency (oxygen and carbon dioxide)

Oxygen and carbon dioxide concentrations in the windrow piles were monitored once a week and measured according to the method described previously, to ensure rapid aerobic decomposition during composting phases. If oxygen supply is limited, microorganisms favour anaerobic conditions that cause high odour potential [40]. Regular turning frequency enhances aeration in the composting material, maintains existing heat and moisture inside the piles, and reduces gas losses especially in low C/N ratio mixtures.

The average results of the monitoring program for all piles are shown in Figure 9. As is clearly seen, the initial concentration of oxygen within the piles body was very low, due to the high rate of biological activities. This can be also seen and proven from the results of CO_2 concentrations in the initial phases, in which the concentrations were very high. As the composting process is progressing, oxygen concentration increased and CO_2 concentrations decreased accordingly. This is attributed to the decreasing rate of biological degradation [41].

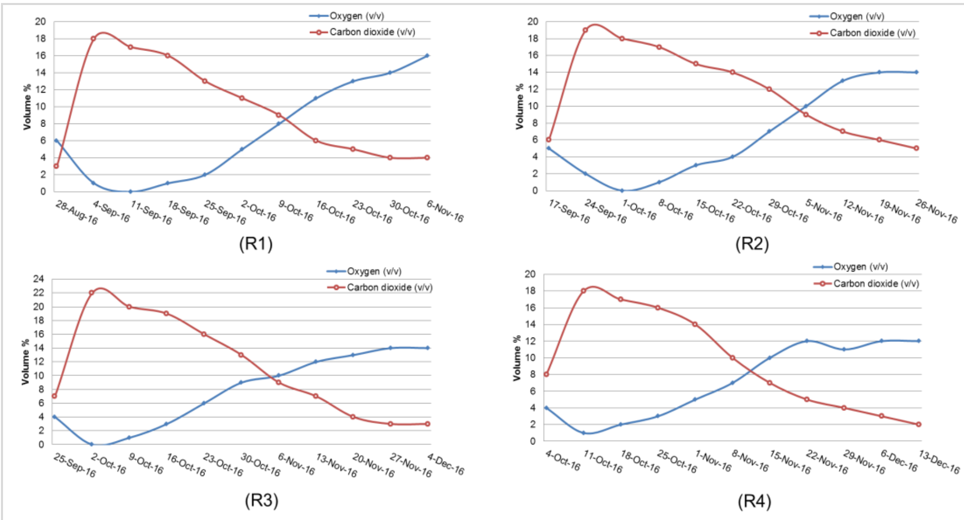

Fig. 9. Average O_2 and CO_2 concentrations for all piles during composting runs

As evident in Figure 9, CO_2 concentrations inside the entire piles immediately increased to around 20% (v/v) during the first week of composting. O_2 concentrations followed an opposite trend during the composting time, declining rapidly to the lowest level (0%) from the start of composting. Thereafter, O_2 concentrations gradually increased as the composting process progressed, reaching the highest levels during the curing phase. The change in trends of O_2 and CO_2 concentrations is attributable to vigorous microbial activity in aerobic composting. Therefore, concentrations of O_2 and CO_2 in an aerobic process function as a monitoring index for provision of sufficient oxygen to the piles via windrow turning practices. Bulky materials such as woodchips are often used to maintain structure and porosity, decomposing much slower than other types of carbon sources, such as sawdust. Furthermore, plant residues used in R1 and R2 had better structure than manure, which was critical in providing porosity and, hence, aeration. Well-aerated mixtures resulted in low turning frequency and high quality products [42].

The concentration of O_2 and CO_2 was considered as an indicator for turning the piles, regardless of the turning schedule previously discussed in the research methodology. If the O_2 concentration was found to be nearing zero in any sampling location, turning was immediately applied, to provide the microorganisms in the pile with the required oxygen. The concentration of CO_2 in the final curing phase of composting (about 3%) clearly demonstrates that existing biological degradation proceeds at a very low rate.

4.7 pH control

Microorganism growth and gaseous loss of ammonia are influenced by pH variations during composting. Therefore, the optimum pH for microbes involved in decomposition lies between 6.5 and 7.5 [25].

The pH is a measure of active acidity in the feedstock or compost and most finished composts will have pH values in the range of 6 to 8; these ranges can be substantially different depending on the kinds of feedstock used. A lower pH is preferred for certain plants, while a neutral pH is suitable for most applications. The pH is not a measure of the total acidity or alkalinity and cannot be used to predict the compost effect on soil pH. The pH value of the compost is important, since applying compost to the soil can alter the soil pH, which, in turn, can affect the availability of nutrients to the plant [43, 44].

The pH profiles of the pile materials during the four runs are shown in Figure 10. It is clearly seen that there was a pH decrease during the first two weeks of composting, where the pH of decomposition was between 0.6 and 7.5. The decrease in the pH values is attributed to the biological activities of the aerobic decomposition, where hydrogen atom (acid) is produced [45]. In spite of the high rate of biological activity during the initial phase of composting, pH values were no less than 6. This can be explained by the high buffering capacity of the composting material, which averts a sharp decrease in the pH values [42]. As composting process is progressing, pH values increased up to 9, and generally stabilised between 7.5 and 8 by the end of the second composting phase. The pH values during the curing stage increased as a result of reduced acid production, due to lower biological activity rates.

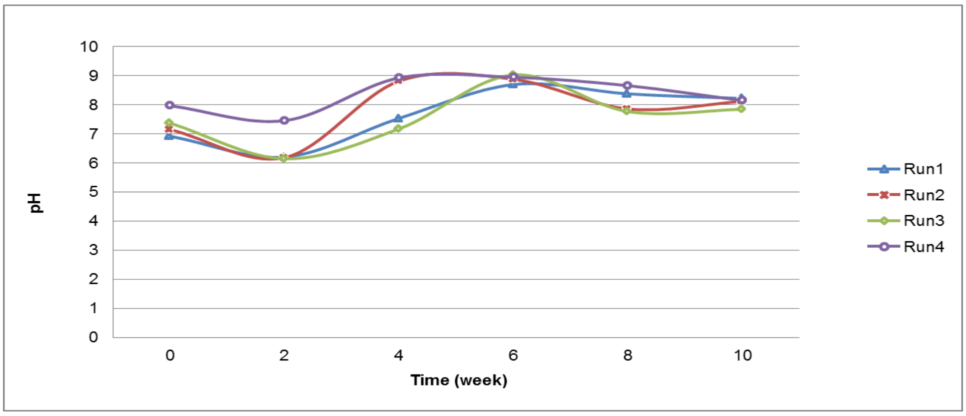

Fig. 10. Average pH profiles during composting runs

4.8 Electric Conductivity (EC) control

Electric conductivity is a measure of the combined amount of salts in the compost: the greater the concentration of soluble salts in the compost, the greater the electrical conductance. Generally, compost soluble salt levels typically range from 1-10ms/cm. Electric conductivity of the compost samples varied from 2.58-4.14 dS/m, with a median value of 2.64 (see Figure 11). Soluble salts can be harmful to plants by reducing water absorption and producing conditions that are toxic. Ideal soluble salt levels will depend on the end use of the compost. Therefore, some compost uses can have higher soluble salts content, such as 12 ms/cm [46], however, greater management is required, depending on the soil to which it is to be added, the amount and frequency of compost addition to the soil, the plant's tolerance to high salt concentrations, and the amounts and frequency of irrigation water or rainfall.

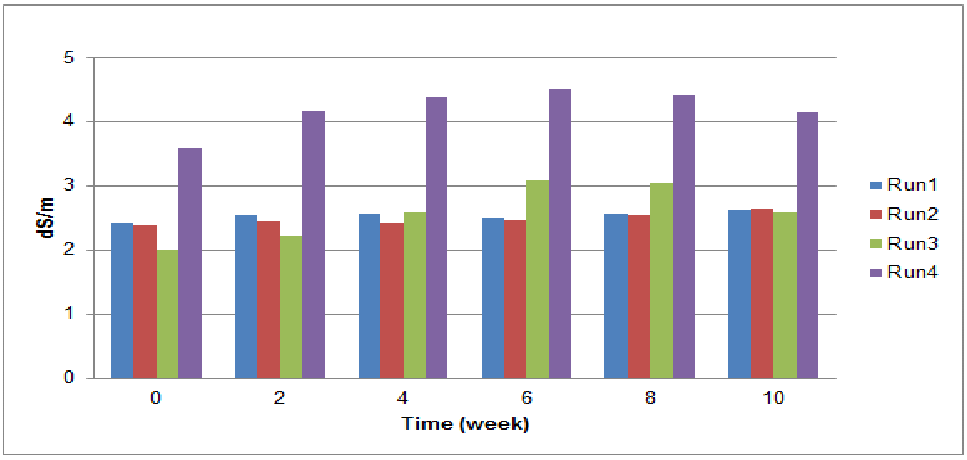

Fig. 11. Average EC values during composting runs

Compared to initial values, the final EC for the composting product by all runs piles showed an increase of 7.3, 9.8, 22.1 and 13,3 % in R1, R2, R3 and R4 respectively. This can be attributed to the mineralisation in the organic material of the waste, and to the EC content of added water.

4.9 Nutrients content

Composts are aerobically decomposed products of organic wastes, such as cattle dung and animal droppings, farm and forest wastes and municipal solid wastes (MSW). Bombatkar (1996) called them a 'miracle' for plant growth. They supply balanced nutrients to plant roots, stimulate growth, increase organic matter content of the soil including the 'humic substances' that affect nutrient accumulation, and promote root growth. In fact, they improve the total physical and chemical properties of the soil [47]. They also add useful micro-organisms and provide food for the existing soil micro-organisms, thus increasing their biological properties and capacity for soil fertility self-renewal [48]. One ton of compost may contain 10lbs of nitrogen (N), 5lbs of phosphorus (P_2O_5), and 10lbs of potash (K_2O).

Bombatkar (1996) reported that compost made from animal manure, particularly from horse and poultry droppings, contains the highest nutrient level among all compost runs. This can be clearly seen in figure 12. The Figure shows an increase in the agricultural beneficial fertilising elements of nitrogen, phosphorous and potassium. A 64, 54, 58 and 62% increase in N concentrations; 38, 33, 23 & 20% increase in P concentrations; and 25, 24, 37 & 11% increase in K concentrations, have been exhibited in R1, R2, R3 and R4 respectively. This increase is due to the reduction in composting volume and the increase the in pile bulk density.

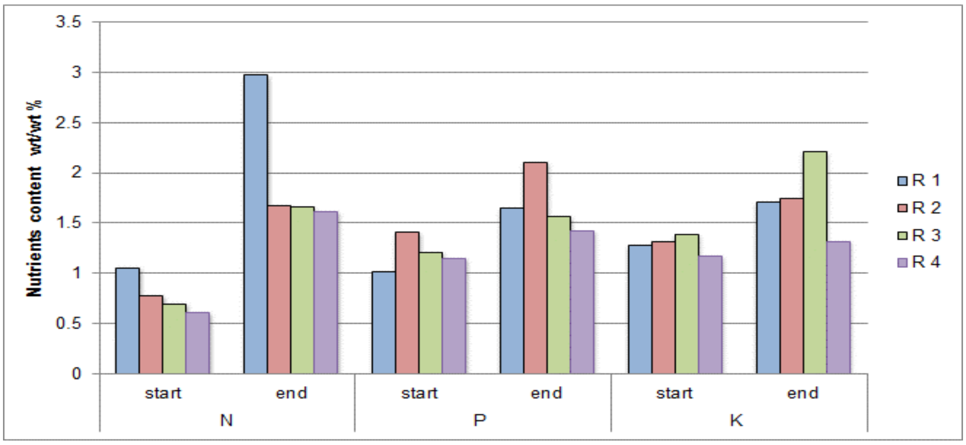

Fig. 12. Nutrients content (wt/wt %) during composting runs

4.10 Pile volume and water consumption during composting

The reduction ratio of the bulk volume was significantly influenced by composting time, decomposition rate, turning frequency and bulking materials that give support for pile structure [49].

As a result of the biological activity, organics in the composting material (substrate) were mineralised and transformed into stable materials and carbon dioxide [50]. Accordingly, this resulted in a reduction in the volume of the composting material (see Figure 13). The pile volumes decreased in the range of 25-35% by the end of composting processes (after 10 weeks), attributed to vigorous microbial activity within the pile.

This reduction in the material volume is offset by an increase in the bulk density, where an approximate 15% increase was achieved. This is considered crucial to further justification for composting, resulting in a 35% reduction in transportation requirements for composted material, in comparison to uncomposted unstabilised organic material.

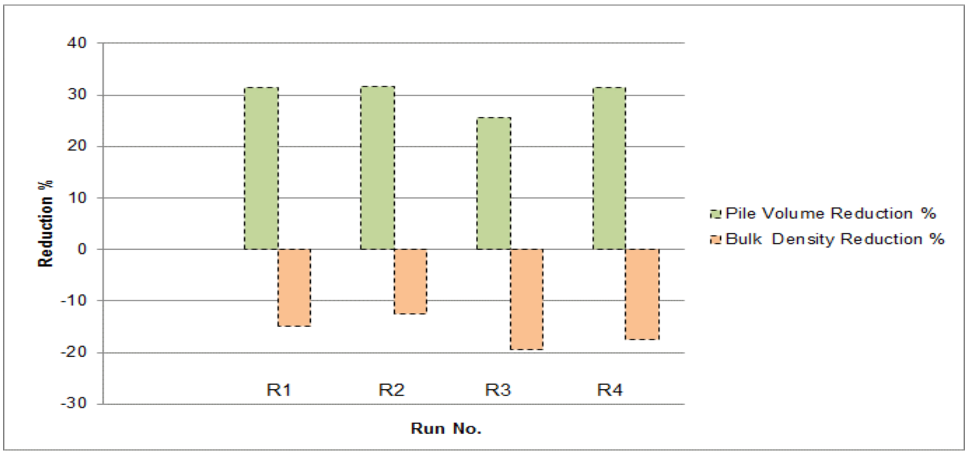

Fig.13. Pile volume and bulk density during composting runs

Water for provision of optimum moisture levels inside composting piles was affected by internal heat generated due to microbial activities and ambient environment. The summary of the initial organic material volume, final composting volume, and water added volume is shown in Figure 14. It is can be seen that the amount of added water (in volume) is more or less equal to the amount of organic fertilizer produced (in volume), so that a 1:1 ratio can be assumed. In other words, the ratio of water added in relation to the amount of raw composting material is about 55% for the four piles.

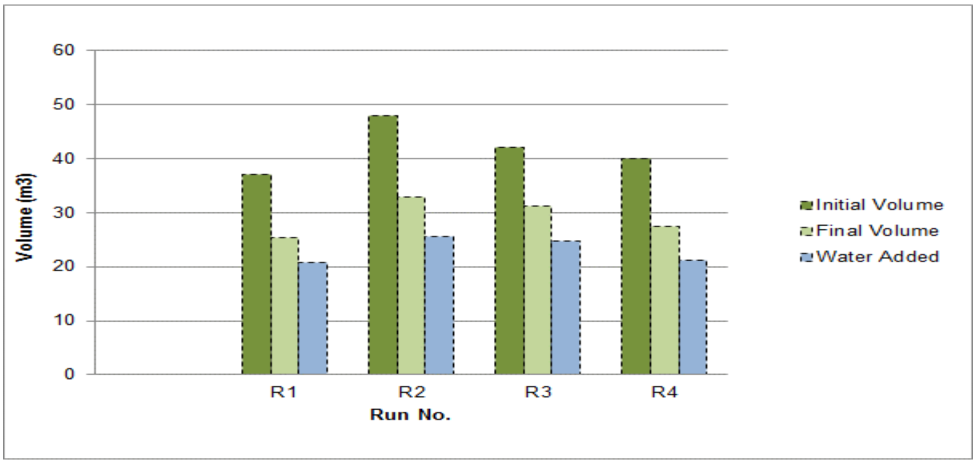

Fig. 14. Pile water consumption during composting runs

4.11 Heavy metals

Heavy metals are trace elements with concentrations that are regulated due to the potential for toxicity to humans, animals and plants. Many of these elements are actually required for normal plant growth. There are many sources of heavy metals within household waste, several of which can pass through mechanical screens designed to remove non-biodegradable matter such at batteries [51]. The results of the heavy metal concentrations in the samples are shown in Table 10 [52].

Table 10. Heavy metal concentrations of compost compared with German standards

Parameter	Range	Averaged limit values of EU countries	
		Class 1	Class 2
Pb mg/kg	2.0 – 9.30	**100**	**150**
Cd mg/kg	0.42 – 0.95	**0.7**	**1.5**
Cr mg/kg	43 – 70	**100**	**150**
Cu mg/kg	44 – 82	**100**	**150**
Ni mg/kg	30 - 59	**50**	**75**
Hg mg/kg	< 0,05	**0.5**	**1.0**
Zn mg/kg	46 – 75	**200**	**400**

High levels of heavy metals represent an obvious concern when the compost is to be applied to food crops [53, 54]. Heavy metals do not degrade during the composting process, and always become more concentrated due to the microbial degradation. Heavy metals in compost products are sourced from the raw materials subjected to composting. Thus, the method of waste collection (i.e., source-separated or mixed collection) and composition characteristics of the raw materials significantly affect the quality of the compost product [55].

Source separation is generally regarded as the most effective and promising method for improving compost quality in terms of metal content [56]. The metal (Pb, Zn, Cu, Cd, Cr, Hg and Ni) contents in source-separated compost shown in Fig. 15 clearly indicate the effectiveness of source-separated collection on metal content control, where the concentrations of all seven heavy metals were significantly lower in source-separated compost.

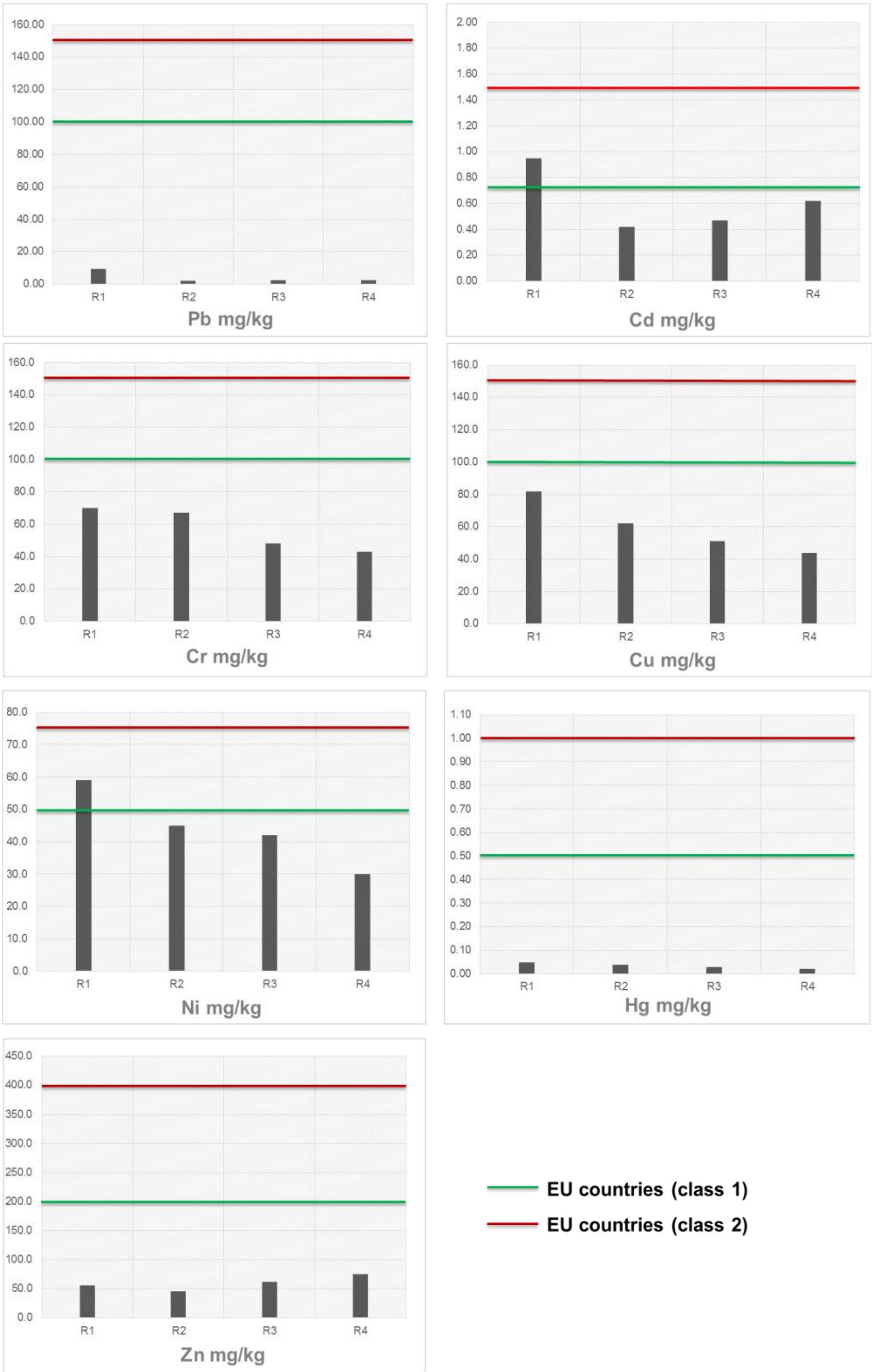

Fig. 15. The concentration of each heavy metal element in the analysed compost samples.

4.12 Organic matter

There is no ideal organic matter level for finished compost. Organic matter (OM) in the samples varied from 19% to 42%, and all of the compost samples had organic matter content lower than the value set by the German standard (BioAbfV), which should be between 15-45% (see Figure 16). Dry compost that is high in organic matter content is difficult to incorporate into the soil because it tends to stay on the surface of the soil.

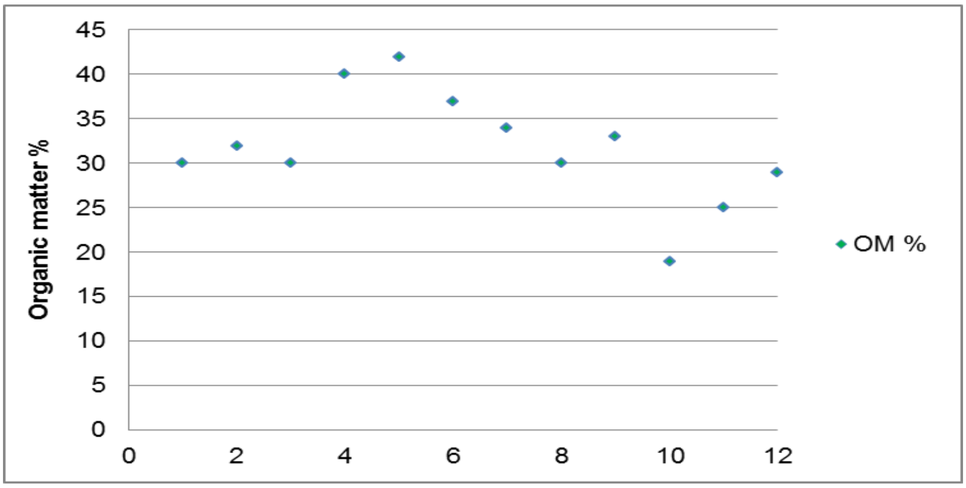

Fig. 16. The results of the organic matter content in the analysed compost samples.

Four samples (one sample from each run) were tested in n=3. The results are averages, with the lowest average value of total organic matter (24.3%) found for R4, formed from one portion of vegetable waste, one portion of cow manure and one portion of poultry manure compost (1V: 1C: 1P), and the highest average value of total organic matter (39.8%) found for R2, from nine portions of poultry manure and one portion of plant residues compost (9P: 1Plant residues). These results are in agreement with Benito et al., (2005) who found the highest value of total organic matter to be about 44% [57].

4.13 Respiration activities

Respiration is directly related to the metabolic activity of a microbial population. Micro-organisms respire at higher rates in the presence of large amounts of bioavailable organic matter, while respiration rate is slower if this type of material is scarce. In the composting process, respiration activity has become an important parameter for the determination of the stability of compost. It is also used for the monitoring of the composting process and is considered to be an important factor for the estimation of the maturity of the material [58].

A wide range of respirometric protocols has been reported based either on CO_2 production, O_2 uptake or release of heat. The most common methods are those based on O_2 uptake. Respirometric assays are affected by a number of parameters including temperature, humidity, and both incubation and pre-incubation conditions. In the European legislation drafts (European Commission 2001), stabilisation means the reduction of the decomposition properties of bio-waste to such an extent that offensive odours are minimised and that respiration activity after four days is below 10mg O_2/gm dm [59-61].

Therefore, this test contributes to understanding stability and maturity from a microbiological basis. Its measurement is used to estimate biological activity in a sample; it refers to a specific stage of organic matter decomposition during or after composting, which is related to the type of organic compounds remaining and the resultant biological activity in the material.

Table 11. Classification of the compost samples analysed for AT4 test [62]

Rotting class	AT4 (mg O2/g DM)	Classification of the samples tested	Product description
I	>40	0 %	Compost raw materials
II	40-28	0 %	Fresh compost
III	28-16	0 %	Fresh compost
IV	16-6	75 %	Finished compost
V	<6	25 %	Finished compost

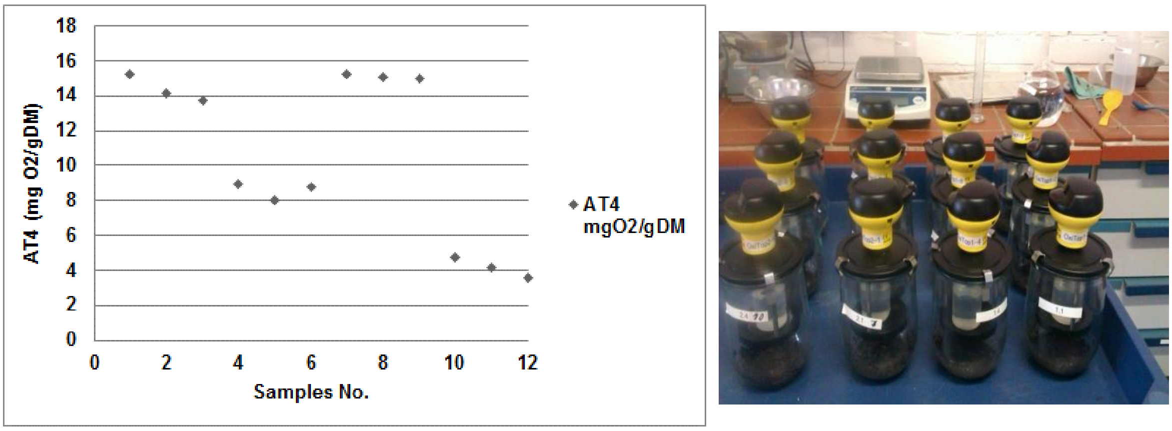

Fig. **17**. The results of the AT4 test for all compost samples included in the study

The stability of any given compost is important in determining the potential impact of the material on nitrogen availability in soil. Most uses of compost require a stable to very stable product that will prevent nutrient tie-up and maintain or enhance oxygen availability in soil. As shown in Table 11, compost respiration in the samples varied from 3.6 to 19.9 mgO_2/g dm (see Figure 17). Accordingly, all of the compost samples appeared to be stable and considered as class IV and V finished product (see Figure 18).

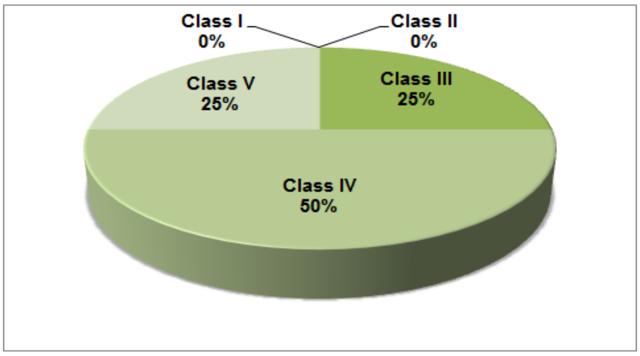

Fig. **18**. Distribution of compost samples according to their rotting degree/class

The results indicated that the compost produced is quite stable and there is no more biological activity, as the organic material was destroyed to form a new stable material (soils) that can be used for agricultural purposes. This also indicates that the compost production process has been performed successfully, under ideal conditions, and within a relatively short time (70 days), which, in turn, reduces the cost.

4.14 Maturation Index (MI) for composting runs

Another way of looking at the stability of the treated waste is defined by the Maturity Index (MI) of the final compost product. Compost maturity generally refers to the degree of decomposition phytotoxic organic substances produced during the active composting phase and to the absence of pathogen and viable weed seeds [63]. The stability or maturity of the final product is of vital importance for successful agricultural application. However, an unstable compost product indicates that microbial activity is sufficiently high that it will cause adverse effects [64]. Since compost has traditionally been used agriculturally, this infers that plant growth will be negatively impacted. In other words, mature compost will exhibit characteristics that indicate completeness of the composting process. Table 12 shows the results of the Mi calculations based on the assumption that all weighing factors are assumed to be 1.

Table 12. Maturation index (M_i) calculations of finished compost products during runs

	Composting runs			
M_i Parameters	**R1**	**R2**	**R3**	**R4**
Initial C/N ratio	**28.0**	**31.0**	**36.0**	**41.0**
$T_{max\ °C}$	64.60	63.80	67.80	64.80
$T_{amb\ °C}$	23.80	19.60	18.20	16.73
$T_{HCP\ day}$	22.00	20.00	21.00	14.00
$T_{LCP\ day}$	50.00	52.00	54.00	56.00
$t_{T\ day}$	70.00	70.00	70.00	70.00
Δ_{CN}	13.00	13.00	15.00	16.00
F_{CN}	15.00	18.00	21.00	25.00
a	1.00	1.00	1.00	1.00
b	1.00	1.00	1.00	1.00
c	1.00	1.00	1.00	1.00
d	1.00	1.00	1.00	1.00
M_i	**2.54**	**2.44**	**2.52**	**2.38**

According to the above table, the Mi values of the entire pile products ranged from 2.38 to 2.54, and composting piles have equal maturation periods. It can be seen from the Mi previously discussed, that those piles with higher Mi reflect the high quality compost. Consequently, this indicates that the composting system was operated under optimal conditions and compost maturation was achieved. It can be concluded, due to the relatively similar values of Mi of the entire piles, that the quality of these products during the four runs is relatively high and similar.This is based on the assumption that maximum temperature achieved, C/N ratio, and active composting time have equal weight in the equation of Mi. Table 13 summarizes the entire results achieved at the end of all runs piles.

Table 13. Final physical and chemical characteristics of composting for all runs

Parameter	R1	R2	R3	R4
Ash Content (%)	44.2	42.5	45.7	41.4
Volatile Solids (%)	55.8	57.5	54.3	58.6
TOC (%)	31.0	31.9	30.1	32.6
TKN (%)	2.98	1.68	1.66	1.62
Total Organic Matter (%)	30.7	39.8	32.1	24.3
C/N Ratio (w/w)	15.0	18.0	21.0	25.0
Moisture Content MC (%)	30.0	27.0	31.0	35.0
pH	8.21	8.11	7.84	8.14
EC (dS/m)	2.62	2.65	2.58	4.14

Total P (%)	1.65	2.11	1.57	1.43
Total K (%)	1.71	1.75	2.21	1.32
Final Pile Volume m^3	25.4	32.8	31.3	27.4
Volume Reduction %	31.4	31.7	25.5	31.5
Final Bulk Density Kg/m^3	520.0	469.0	485.0	690.0
Bulk Density Increase %	14.8	12.5	19.46	17.55
Water Added m^3	20.7	25.5	24.8	21.2
m^3 water / m^3 manure	0.56	0.53	0.59	0.53
Heavy metals mg/kg				
As	< 5	< 5	< 5	< 5
Pb	9.30	2.00	2.40	2.50
Cd	0.95	0.42	0.47	0.62
Cr	70.0	67.0	48.0	43.0
Ni	59.0	45.0	42.0	30.0
Hg	< 0,05	< 0,05	< 0,05	< 0,05
Zn	56.0	46.0	62.0	75.0
Cu	82.0	62.0	51.0	44.0

Overall, results of the experiment showed that compost with acceptably chemical properties (OM, TOC, TKN, total P, total K, heavy metals) and physical properties (bulk density, moisture content, etc.) was produced . These findings indicated that composting was carried out successfully under optimised conditions. It can be observed from the findings that the quality of the produced compost depends largely on the level of the C/N start-up ratio and also the quality of its constituents within the mixture.

5. Conclusions

Modern societies need to optimise exploitation of recycling of solid waste, and compost production for improving soil fertility is a sustainable option for the waste recycling market. Composting is an easy technique and becoming a more acceptable and economical approach for managing all types of biodegradable organic wastes.

Monitoring and control of the composting parameters is one of the most effective tools in the production of stable organic fertilisers.

Results of the experiment showed that composting of animal manure with plant residues, vegetables residues and bulking agent (sawdust) was carried out successfully under optimised conditions.

Co-composting was performed at different C/N ratios ranging from 25 to 45, at moisture content of 55%. The windrow piles were mechanically turned using a special compost turner. Temperatures were rapidly increased from ambient temperature up to 60-70 ºC during the first week; this range is enough for pathogens and weed seeds termination. Mixtures of poultry and cow manures with 10% sawdust had more thermophilic temperature development than mixtures of street plant residue and manure. The windrows needed 10 weeks to complete the composting phases and produce stabilised products. The initial C/N ratios which ranged from 30 to 40 showed optimal composting processes and resulted in final products with relatively high maturation index (Mi) based on the proposed weighing factors. Furthermore, high C/N ratios of more than 40 resulted in low temperature development and slow degradation process with relatively low Mi. The reduction of C/N ratio during the composting process ranged from 38-46% and the highest result was achieved in the piles with high initial nitrogen content (low initial C/N ratio). Mass losses during composting resulted in total pile volumes decreased to a range of 25-35 %. A 15% increase in the bulk density also occurred. A 1:1 ratio was assumed for the amounts of added water (in volume) in relation to the amounts of produced organic fertiliser (in volume). Final product quality was exhibited by significantly lower concentrations of all seven heavy metals (Pb, Zn, Cu, Cd, Cr, Hg and Ni) in all piles. Compost respiration in the samples varied from 3.6 to 19.9 mgO_2/g dm. All of the compost samples appeared to be stable and considered as finished product of class IV and V.

Poultry and cow manure, with the possible addition of structural material (sawdust), proved to be excellent input materials for composting processes. Use of vegetable and plant residues showed high potential as input material in the composting process, especially in proper mixing with poultry manure.

One conclusion is that the source separation, combined with effective composting process parameters, are regarded as the most effective and promising method for production of high grade compost. Another deduction is that the periodic mechanical turning using windrow method improves the gaseous exchange within the windrow piles, speeds up the decomposition rate, maintains uniform homogeneity, and hence minimises gaseous losses (especially ammonia).

Overall, results showed that the separated organic waste approach proved to be efficient for the compost produced by this pilot project and holds the potential for a wider application, but national laws and regulations in terms of organic waste collection, transfer and treatment, as well as standard values for defining compost quality for agricultural use, should be determined and enforced in Jordan.

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