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Effect of Drilling Fluid Components on Composting and the Consequences for Mud Formulation.

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Abstract

Composting is a well-established, biological technique in which bacteria and other microorganisms degrade and convert organic matter to humus and microbial biomass. Composting can also be utilized to degrade the oil component of drill cuttings, but the choice of drilling fluid coating these cuttings will affect the quality and composition of the compost end product as well as reaction rates and the final concentrations of hazardous materials. Drilling fluid formulations can be designed to optimize the composting rate and minimize hazardous residues, but the fluids technical performance, cost and availability are also critical.

This paper describes the results of laboratory investigations into the effect of drilling fluid chemistry and organic amendments on composting rate and end-product quality together with the consequences for large-scale composting operations and their likely impact on drilling operations.

Experiments have shown that the optimum cuttings: amendments ratio is 1:1, with a variety of organic amendments being suitable for use in the process.

Hydrocarbon loading and hydrocarbon type affect reaction rate but all base fluids tested (linear paraffin's are the fastest, diesel was the slowest) were degraded to less than 1% TEH in the "mature" compost. Little effect on composting efficiency was seen by changing the drilling fluid internal phase salt type or weighting agent type.

Introduction

Cuttings are pieces of formation rock produced by the drill bit that are returned up the annulus of the hole suspended in the drilling fluid. Solids-control equipment (*e.g.* shakers, centrifuges) at the drill site remove the solids from the fluid and return the valuable drilling fluid back to the active system in a process that reduces the waste at source. When drilling with oil- or synthetic-based drilling fluids (invert emulsions), the fluid coating the cuttings typically contains ~10% hydrocarbon. With increasing environmental constraints on the discharge of oil- or synthetic-based drill cuttings, various treatment options are available to reduce the hydrocarbon content and allow disposal or re-use. Bioremediation techniques such as composting are becoming increasingly important as this allows the conversion of the waste into a useful product. Such technologies allow recycling and reuse and sit near the top of the waste management hierarchy (Figure 1) which is preferential when deciding on the means of drill cuttings disposal. Bioremediation can be adapted to co-compost drill cuttings with the microbial flora and fauna being able to utilize the hydrocarbon component of the drilling fluid as a carbon source for growth. Through this process, the hydrocarbon content of the drill cuttings is reduced in a natural process that converts the cuttings into a non-toxic and potentially useful end product.

Composting Mechanisms and Reactions

Microbiological activity during the process of composting generates metabolic heat that divides the composting process into four stages.

During the mesophilic stage (1-2 days) indigenous micro-organisms (bacteria and fungi) multiply rapidly and the temperature increases from ambient to ~40°C.[1] The mesophilic bacteria break down the soluble, readily degradable material[2] and as organic acids are produced, the mass becomes increasingly acidic.[1]

As temperatures increase above 40°C, the composting reaction enters the thermophilic stage which can last a few days to several months. The indigenous mesophile population starts to decline and the thermophilic bacteria (particularly *Bacillus* and some fungi) take-over.[2] During this stage, high temperatures accelerate the breakdown of proteins and fats and some of the more complex carbohydrates. The pH starts to turn alkaline as ammonia is liberated.[1] Thermophiles continue to grow increasing the temperature to ~60°C, where fungi start to be deactivated.

Above 60°C, the composting is continued by actinomycetes (slower growing than bacteria and fungi in mesophilic stage)[1] which play an important role in degrading complex organics such as cellulose, lignin, chitin and proteins.[3] Temperatures >60°C are also useful in controlling thermo-sensitive pathogens to crops, animals and man and in killing off weeds and seeds that will be detrimental for land use of the product. The reaction rate decreases as more resistant materials are encountered and a temperature maximum is reached when the rate of heat generation equals the rate of heat loss.[1]

As heat generation decreases further the compost enters the cooling stage, where the compost is said to have reached stability. The easily convertible material has been decomposed, the major O_2 demand has been met and the production of odorous vapors has declined. During this stage the pH drops slightly but remains alkaline. Thermophilic fungi re-invade the mass from the cooler regions and with the actinomycetes attack the long chain polysaccharides, celluloses etc. and degrade them into simple sugars. The rate of energy release is very small and the temperature of the mass falls to ambient.[1] Compost is typically left to mature (the 4th stage) for several months, prior to use as a horticultural or agricultural growth medium, allowing complex chemical reactions to occur between lignin residues and proteins of dead microorganisms to produce humus. The final pH is slightly alkaline.[1]

Many factors govern the rate and efficiency of the composting process. A summary of the optimum conditions proposed for composting is given in Table 1. Composting is an aerobic process and adequate aeration will supply the oxygen essential for the aerobic composting micro-organisms and also removes CO_2, moisture and heat (evaporative heat transfer) from the compost heap. Adequate aeration can be achieved by turning or more advanced engineered solutions. Optimization of the blend particle size can ensure a high surface area for microbiological attack yet prevent compaction and allow diffusion of air into, and CO_2 out of, the mass.

The requirements for C, N, P, K and trace elements for the bacterial growth are normally met by the organic material to be degraded. Only the C:N ratio and occasionally the P level require adjustment.[2] An initial C:N ratio of 25:1-30:1 has been suggested as optimum but as the composting process proceeds the C:N ratio will fall to ~10:1 as CO_2 is released and C is assimilated in microbial cells.[2] The required C:N ratio can be achieved by the correct blending ratio for the raw ingredients.

The moisture content of the compost blend is crucial as water is the medium for chemical reactions and water is required for micro-organisms to move about. Optimal water content is 50-60% allowing optimum biological reaction without saturating the air spaces of the compost thereby preventing anaerobic conditions. This can be achieved by correct blending of the raw ingredients and supplemental addition of water throughout the composting reaction as required. Although high temperatures are considered necessary for good composting, it should be noted that composting is suppressed at temperatures >60°C as growth of the micro-organisms is inhibited. It has been suggested that 55°C would be an optimum temperature for composting[1]. Cooling or insulation may be required to control temperature.

Composting Drill Cuttings

Successful composting of drill cuttings requires a source of bacteria and the blending of the cuttings with organic materials to provide the correct carbon, nitrogen and moisture ratios.

In order to ensure an efficient composting reaction and degradation of the hydrocarbon component of the cuttings as well as to ensure that the end-product meets all relevant legislation, the quality and composition of both the starting material and the end product need to be controlled.

The addition of the drilling fluid and its chemical constituents as well as large amounts of inert material (in the form of formation rock) will have consequences for the composting process. The choice of drilling fluid chemistry not only will affect the quality and composition of the compost end product, but also influences reaction rates and final concentrations of the drilling wastes. Drilling fluid formulations can be designed to optimize the composting rate and minimize hazardous residues, but the fluids technical performance, cost and availability are also critical.

Oil-based or synthetic-based drilling fluids consist of a continuous phase of hydrocarbon whose chemical composition varies according to logistics, legislation and environmental limits as well as fluid properties, *e.g.* viscosity and flash point. The fluids used vary in composition and structure and may contain linear, branched, saturated, unsaturated and aromatic hydrocarbons, covering a range of molecular weights. The precise nature of the hydrocarbon affects the biodegradation potential. For molecules of the same molecular weight, decreasing the degree of aromaticity and branching causes the base fluid to become more biodegradable and less toxic. For example, the paraffinic components of diesel will degrade quicker than the aromatic, branched and cyclic hydrocarbons present. Furthermore, lower molecular weight structures tend to be easier to biodegrade, although in some circumstances they can be more toxic. Regulations concerning the quantities of organic contaminants permitted in composts vary. Some legislation quote permitted quantities of specific organics, *e.g.* PCBs, PAHs, Dioxins, while others quote in addition a hydrocarbon loading. For example Austria permits 3000-mg/kg hydrocarbons, 6-mg/kg PAH and 1-mg/kg PCB.[4]

The micro-organisms that can utilize these non-water soluble carbon sources adapt to develop mechanisms for the assimilation of these materials. These include:[5,6]

- Utilization of the chemical in the water phase
- Production of a surfactant to solubilise the hydrocarbon into droplets of <1 μm that can then be

assimilated (pseudosolubilisation)

- Formation of a microbial population on the surface of the hydrocarbon droplets

Drilling fluids also contain an internal phase of brine, used to achieve a specific water activity and control the osmotic movement of water between the drilling fluid and formation. The salt typically used for this purpose is calcium chloride but the use of chloride-based salts creates potential disposal problems for any oilfield waste generated with this type of fluid; especially as electrical conductivity is one of the key parameters considered by consent limits and disposal. The replacement of the calcium chloride with alternative salts has been investigated and it is now possible to formulate drilling fluids with potassium acetate, potassium formate, calcium ammonium nitrate and calcium nitrate internal phases that give equivalent technical performance to the calcium chloride systems. An added advantage of using salts such as calcium ammonium nitrate is that if the waste is disposed to land, the salt may add beneficial nutrients, while the acetate and formate salts also have to potential to biodegrade. High salinity is often a cause of compost problems causing damage to plants, *e.g.* root rot, wilting, yellowing of leaves. Plants differ greatly in their sensitivity to salinity. Regulations governing the conductivity of composts vary between countries. For example in some countries there is no limit set whereas in places like Australia, compost loading rates are set for composts of different salinities and whether they are to be used for growing salinity sensitive or tolerant plants.[4]

Weighting material is added to drilling fluids to adjust the density as required by the drilling operations. The most commonly used weighting agent is barite ($BaSO_4$) but hematite (Fe_2O_3) and ilmenite ($FeTiO_3$) can also be used for specific operations. As these materials are natural ores, they contribute heavy metals to the drilling fluid and thus may add to the heavy metal content of bioremediation products. Although these metals may not be in a bioavailable form, composting regulations place limits on the amount of heavy metals permitted in composts. The specific criteria vary between locations.

Various other additives are present in the drilling fluid to control the physical properties – namely emulsion stabilisers, pH adjusters, wetting agents, viscosifiers and fluid-loss-reducing agents. However, the specific chemicals used often vary between locations and it is assumed that in most cases their environmental impact is negligible compared to the effects of hydrocarbons, salts and heavy metals.

The final effect of adding drill cuttings to a compost blend is the high amount of inert inorganic material present. The presence of clays may be beneficial if the compost was added to a clay-deficient soil, but the quantity of the cuttings present must be controlled to ensure an efficient process.

In the following sections the effect of these variables on the composting process and end-product quality is discussed together with the consequences for large scale composting and for drilling operations.

Test Methodology

Experiments to investigate the effect of drilling fluid chemistries and cuttings loading on composting rate were performed using a simple box composter – an insulated box assembled from polystyrene ceiling tiles with 4 test compartments. This design has several advantages: low evaporative drying and high heat retention due to a high height: width ratio and a high sample throughput.

Compost mixtures were prepared using organic amendments (chicken manure as a nitrogen source, sawdust and woodchips as a carbon source). In some experiments, the degradation of the drilling fluid component was investigated in the absence of cuttings material and therefore the component under test was added directly to the organic amendments. Where cuttings were used, Oxford Clay sized to <4 mm was coated in an appropriate drilling fluid to achieve a 10% hydrocarbon content to simulate cuttings as obtained in the field. The cuttings and organic amendments were mixed together by hand. The carbon and nitrogen content of each ingredient was taken from literature and the ingredients blended to give a C:N ratio of 30:1 and a moisture content of ~50%.

The compost blends were added to the box composter and left for at least 28 days. During this time several parameters were monitored in order to determine the progress of the composting reaction:

- ***Moisture Content*** – Compost samples were analyzed using a Mettler PE 360 IR balance. The compost was heated at 100°C for 30-second periods until no further weight change was measured.
- ***Temperature* -** The temperature of the compost was measured at three positions using a calibrated digital thermometer and then averaged. Temperature monitoring was performed twice daily.
- ***Total Extractable Hydrocarbon (TEH) Content*** - Sub-samples of compost were taken using a coring device and frozen. The samples were then ground, sieved to 1-4 mm, heaped and quartered until appropriate sized, representative samples were achieved. Hydrocarbons were extracted using dichloromethane and sonication and concentrated by rotary evaporation and under nitrogen as per EPA-3550B.[7] The sample was then analysed by GC-FID. The GC used was a Star 3400 fitted with a JW DB1 megabore column.

Composting experiments were designed to investigate the effect of various parameters: base fluid chemistry and concentration; salt type and concentration; weighting-agent type and cuttings loading.

The Effect of Cuttings Loading on Composting

The concentration of cuttings in a compost blend will affect the physical nature of the end product and the efficiency of the composting reaction. In order to determine an optimum cuttings loading, Oxford clay cuttings (<4 mm) coated in a linear paraffin drilling fluid were added to organic amendments (chicken manure and sawdust) at different ratios between 0.1:1 and 3:1. Repeat tests were performed on compost blends containing >1:1 cuttings: amendments where sawdust was replaced by a 75:25 blend of sawdust and woodchips in order to increase the particle size of the blend, increase air-flow and decrease cuttings compaction. The composting reactions were allowed to continue for 30 days.

Comparison of the compost mixture containing a 1:1 blend of cuttings: amendments with that containing no cuttings but the same concentration of hydrocarbon shows that the addition of cuttings slows the initial temperature rise and decreases the maximum temperature of the compost (Figure 2). This may be because the drilling fluid coating the cuttings is not uniformly distributed throughout the mixture but more localized round the cutting particles. It may also suggest that the oil is less bioavailable in this form.

Increasing the cuttings loading results in an increase in the maximum temperature reached and extends the length of the thermophilic stage (Figure 2). This can be explained by an increase in the drilling fluid content of the compost and therefore an increase in the available hydrocarbon to be used as a carbon source.

The presence of cuttings did not significantly hinder the biodegradation process as the TEH level of the compost containing no cuttings decreased at a similar rate to when cuttings were present (1:1 ratio) (Figure 3). The time to reach 1% TEH and 0.1% TEH in the compost was the same in both cases (8 and 10 days respectively). Even at concentrations up to 3:1 cuttings: amendments, significant TEH degradation was seen however reaction time was increased. An increase in the cuttings loading from 1:1 cuttings: amendments to 3:1 increased the time taken to achieve 1% and 0.1% TEH from 8 to 10 days and from 10 days to 29 days respectively. Therefore the economics of increased reaction time would have to weigh against the ability to treat larger volumes of drilling waste.

An additional effect of adding increasing quantities of cuttings to the compost mixture is to increase the clay content. With the moisture of the compost being maintained at 50%, the Oxford clay was softened and with ratios of cuttings >1:1 cuttings: amendments caused the compost to clump and compact. It was postulated that increasing the particle size of the compost by the addition of woodchips would decrease this tendency to compact and permit increased aeration of the composting blend. However no significant improvement in terms of product quality or reaction rate was observed. Although no serious effect on the hydrocarbon degradation was seen on the laboratory scale, on a large scale clumping and aggregation could cause logistical problems and may hinder bacterial degradation of the hydrocarbons by causing anaerobic pockets. The end result would impact the final quality of the end product although high solids loading could be used to produce a product that may be suitable for addition to low clay soils or where the compost is being used as a bulking agent or land fill cover instead of as a fertilizer.

It is therefore recommended that 1:1 cuttings: amendment ratio would be most suitable to maintain reaction rate and end product quality. However, field experience and costing will confirm if this is economically viable and the best option for the composting process.

Effect of Base Fluid Type on Composting

The effect of different base fluid types and concentrations on composting rate and end-product quality was investigated.

Effect of increasing base fluid concentration - Linear paraffin (LP) with a C_{11}-C_{17} carbon distribution was added to compost blends prepared with chicken manure and sawdust at 0-20% w/w. Other mud ingredients and cuttings were omitted from the blend to eliminate any interference effects. The addition of increasing amounts of LP increased the C:N ratio of the compost and this increase in available C should encourage bacterial/fungal growth.

The temperature profile of the compost blends (Figure 4) shows that all the composting mixtures heated above room temperature. Formulations containing 0-5% LP did not reach temperatures equivalent to the thermophilic stage of composting (40-60°C).

When the LP concentration was increased to 10-20%, temperatures up to ~50°C were obtained after day 7, with the thermophilic stage being extended and the maximum temperature being increased as the LP concentration increased. Fungal growth was observed consistent with the compost being in the thermophilic stage of composting where the proteins and fats and complex carbohydrates are broken down.

The TEH data from these compost experiments (Figure 5) showed that the hydrocarbon content of the compost is decreased during the composting reaction with most being lost during the first 7 days of composting. After 28 days, a 94-97% reduction in TEH was observed with final hydrocarbon concentrations being 0.001% to 0.3%. The higher the initial hydrocarbon concentration, the higher the final concentration after 28 days but it is likely that the remaining hydrocarbon would be degraded by extending the compost reaction time.

Comparison of the temperature profile and hydrocarbon degradation curves shows that most of the TEH decrease occurs during the mesophilic and thermophilic stages of composting but the decrease continues all-be-it at a slower rate, into the later stages.

Effect of Base Fluid Type - The base fluids tested were a Linear paraffin (LP), Enhanced Mineral Oil (EMO), Low-Toxicity Mineral Oil (LTMO) and diesel. Compost blends were prepared with chicken manure and sawdust and the composting reaction was allowed to continue for 30 days. The temperature profile (Figure 6) shows that initial temperature increases were similar in all cases but the different base oils caused a change in the profile between Days 3 and 15. The presence of the LP, suspected to be the most easily biodegradable due to the presence of only linear hydrocarbon components, showed the longest thermophilic stage and the highest maximum temperature (>40°C). As the quantity of branched, cyclic and aromatic components increased, the maximum temperature was lowered and the time taken to reach ambient temperature was decreased. Diesel, having the largest quantity of "difficult to degrade" components gave the flattest temperature profile. Therefore, the temperature profile suggests that the order for ease of oil biodegradation during composting is, from easiest to hardest, LP>EMO/LTMO>diesel. This concurs with our knowledge of the biodegradation potential of these hydrocarbon chemistries.

TEH concentrations (Figure 7) show that the LP is quickly degraded within the first 10 days, with slower degradation occurring after that. The LTMO showed a steady decline over the 30-day test period with concentrations of the EMO and diesel decreasing slightly initially but not degraded significantly with further time. Examination of the GC traces (not shown) indicates that the linear components are degraded with time, but the "humptane" (i.e. the area of undistinguishable peaks) remains and is difficult to degrade.

Effect of Base Fluid Type as Drilling Fluid Coated Cuttings – Long Term Studies - Following on from the previous investigation, the degradation of base fluids was investigated over longer periods of time.

For the purpose of these tests typical drilling fluids made with the various base fluids (diesel, LTMO, EMO, LAO and LP) were coated onto Oxford clay cuttings prior to addition to the compost amendments. A 1:1 ratio of cuttings:amendments was used, the amendments comprising of chicken manure, sawdust and woodchips. As the previous experiment has shown that after 28 days significant quantities of TEH were still present in the compost with some base fluids, the duration of the experiment was extended to 112 days in order to investigate if, given an increased reaction time, the harder to degrade components of some of the fluids would be remediated.

The temperature profile of the compost blends was similar to that seen in previous tests (Figure 6). The extended reaction time allowed for some maturation of the compost and at this stage the temperature profile followed that of the room temperature. In the presence of the linear paraffin, the most easily degraded base fluid, the compost heated to the highest maximum temperature (40°C). The temperature profile suggested that the preferential degradation order is LP-, LAO-, EMO-, LTMO- then diesel-based drilling fluids.

Examination of the hydrocarbon degradation rate (Figure 8) shows that the LP-, LAO- and LTMO-based drilling fluids degraded to <1% with 6-7 days. Extension of this time period to 19 days and 40 days allows degradation of diesel- and EMO-based drilling fluids to <1% respectively. The long reaction time required for the EMO, despite being a cleaner fraction of diesel in terms of aromatic content, may be due to a higher proportion of branched hydrocarbons. After the 112-day test period, (typical municipal composting times including maturation are 6-12 months), all drilling fluids were degraded to less than 0.1% TEH. Therefore, although the synthetic base fluids show faster degradation rates, the typical composting lifespan including maturation would allow sufficient reaction time for the degradation of all drilling fluids for the base fluid types tested.

Effect of Salts on Composting

Effect of Chloride Contaminated Drilling Fluids – Even if drilling fluids are formulated without a chloride salt, brine flows encountered during the drilling operation can lead to an influx of salt and associated water. In order to simulate this, a linear paraffin drilling fluid was spiked with 10% v/v seawater, 10% v/v saturated NaCl solution and 25% v/v saturated NaCl solution, before mixing and emulsification on a Hamilton Beach mixer. The chloride content of these fluids was determined using standard oilfield test protocols, as per API 13B-2.[8] These drilling fluids were then coated onto Oxford clay cuttings (up to 10% oil-on-cuttings) and composted using a blend of chicken manure, sawdust and woodchips, to achieve a 30:1 C:N ratio and 50% water. The cuttings: amendments ratio was 1:1. Composting reaction was monitored over a 28-day period.

The addition of salt had little effect on the temperature profile or on the hydrocarbon degradation and typical values as previously seen for composting LP fluids were observed. No effect of mud salinity (chloride concentration) was seen on the time taken to reach 1% and 0.1% hydrocarbon concentrations (8 days and 16 days respectively).

Effect of Alternative Internal Phase Salts - The effect of using drilling fluids formulated with different internal phase salts was investigated – calcium chloride, potassium acetate, potassium formate, calcium ammonium nitrate and calcium nitrate were tested. Drilling fluids were formulated using these salts to achieve the same internal phase salinity, using a LP-based fluid.

Compost mixtures were prepared using chicken manure, sawdust and woodchips at a 1:1 ratio to cuttings coated in the specific drilling fluid. When the internal phase salt of the drilling fluid did not contain nitrogen, the compost mixture contained an increased concentration of manure to achieve the correct C:N ratio. The composting reaction was allowed to run for 30 days.

All compost blends generated heat and passed through the thermophilic stage of composting (Figure 9). Calcium nitrate showed a lower maximum temperature compared to the other salts suggesting a poorer composting reaction. All the other salts showed very similar temperature profiles suggesting a normal composting reaction.

Hydrocarbon (LP) degradation profiles were similar for all salt blends and typical of those seen in previous studies with time to degrade the hydrocarbon from ~4% to 1% TEH being 6 – 7 days with a further 10 – 16 days required to reduce the TEH to 0.1%. Therefore, it is suggested that all salts are suitable for use in composting.

At the completion of the experiment, the conductivity of the composts prepared was determined according to BS EN 13038:2000 "Soil Improvers and Growing Media – Determination of Electrical Conductivity".[9] The basic methodology involved adding 250 mL of compost to 1250 mL of distilled water and shaking in an orbital incubator at 150 rpm for 1 hour. After this period the mixture was filtered using an API filter press and the conductivity of the filtrate determined using a WPA CM35 portable conductivity meter. Elements contributing most to electrical conductivity are sodium, potassium, chloride, nitrate, sulfate and ammonia.[10] Table 2 shows the conductivity data for the different compost blends. It can be seen that the compost prepared using mud with a calcium chloride internal phase gave the highest conductivity. Compost prepared with potassium acetate and calcium nitrate gave relatively low electrical conductivity values. This may be due to utilization of these salts during the biodegradation process and a lower contribution to the overall electrical conductivity. However, it must be considered that, although the compost blends were formulated to a C:N ratio of 30:1, the concentrations of the individual ingredients varied. This will also impact the final conductivity measurements. Australia places restrictions of compost usage based on conductivity (Table 3), and compared to their standards, all of our compost blends would be permitted a treatment rate of <2.5 L/m^2 for sensitive plants and <10 L/m^2 for tolerant plants.[7]

Effect of Weighting Agent Type

Drilling fluids were formulated based on LP with no weighting agent or barite, hematite and ilmenite. Compost was prepared using chicken manure, sawdust and woodchips with cuttings: amendment ratio of 1:1 The composting reaction was monitored for 28 days.

All blends passed through the mesophilic, thermophilic and cooling phases of composting as typically seen and no effect of weighting material type was observed. Maximum temperatures achieved were ~45°C with 10 days being required to pass through the mesophilic, thermophilic and cooling stages. Correspondingly, little difference in hydrocarbon degradation was seen between the different blends. All composting mixtures achieved <1% oil in 7 days and final hydrocarbon concentrations of 0.1 – 0.5% after 28 days.

On completion of the test, the heavy metals content was determined by ICP-MS (Figure 10). The values are compared to the lowest permissible limits quoted as specifications for compost in Texas (TNRCC Grade 1 and 2), Colorado and the UK.[7] It can be seen that all compost blends met the required specifications. Table 4 shows the heavy metals concentrations of the weighting materials themselves. It can be seen that the barite material had higher quantities of lead, zinc and mercury compared to ilmenite and hematite while the hematite and ilmentite showed high amounts of chromium. This is reflected in the heavy metals concentrations of the composting blends. However, all blends met the regulation limits and would therefore be suitable for use.

Composting Using Various Organic Amendments

For all previous experiments the composting blend was based on chicken manure, sawdust and woodchip organic amendments. However, the availability of such amendments is location specific and a series of experiments were run to test a range of other amendments that would be suitable for composting reactions. The use of alternative manure (bacterial) sources was investigated by using horse manure and chicken manure. The sawdust and woodchips typically used as a carbon source and a bulking agent were replaced by straw in some experiments. One experiment simulated typical municipal waste compost, using no animal by-products. In this case a blend of shredded vegetable matter (carrots, potatoes, apples, lettuce and paper) was mixed at a 1:1 ratio with shredded plant material. The degradation of a LP-based drilling fluid on Oxford clay cuttings at 1:1 cuttings: amendments ratio was investigated over a 28-day period.

The temperature profile of the compost blends (Figure 11) shows that the blend containing straw gave a low maximum temperature. This is most likely due to heat loss in our small-scale compost boxes, as the straw gives the blend considerable air spaces for convection and cooling. The municipal waste blend showed initially a fast increase in temperature but achieved a maximum temperature similar to the other blends.

The hydrocarbon concentration (Figure 12) of all blends was reduced to <0.1% within the 28-day time period, except the blend containing straw. Results from previous longer term studies suggested that the hydrocarbon concentration of this blend will decrease with an extension in the reaction time. This slower reaction corresponds to the low-temperature profile seen.

Conclusions

The data presented details the effect of various drilling fluid components on the composting reaction as well as the physical effects of adding drill cuttings to a compost mixture.

Linear fluids degraded faster than branched or cyclic/aromatic materials and it is possible to compost a range of different drilling fluids and cuttings having different base fluids, internal salts and weighting agents and using a variety of organic amendments.

The findings have impacts on the operation of the composting plant and also on drilling. When deciding on a suitable drilling fluid, an integrated approach to identifying technical requirements and the need for an efficient composting process will result in successful drilling with reduced environmental impact.

Consequences for Composting Operations - When considering the use of composting as a remediation technique for oil- or synthetic-based drill cuttings, the effect that the cuttings themselves and the chemical components of the drilling fluid have on the composting rate and the ability to produce a high quality end product that meets all environmental legislation for compost must be considered.

Firstly, the choice of the correct starting ingredients for the compost blend is essential. Ingredients should be chosen from a local source (to avoid large transportation costs) and blended such that a C:N ratio of ~30:1 is achieved. The data presented here has shown that various blends of organic material and drill cuttings can produce a composting reaction and promote hydrocarbon degradation. Ultimate choice of ingredients will depend on local availability and cost. Ideally, the use of waste streams from other industries, *e.g.* agriculture, paper manufacture, will provide an environmentally responsible approach to the sourcing of the required amendments. Although our initial tests focused on the use of chicken manure as a source of nitrogen and bacteria, other manure sources are suitable. However, the use of animal by-products is regulated in some countries and for ease of permitting and monitoring etc, non-manure sources may be preferred. Hydrocarbon-degrading bacteria are ubiquitous in the environment and do not need to be supplied as a manure or as a purposefully added bacterial culture. For example, our data presented for the use of municipal waste (garden and vegetable matter) showed that composting and hydrocarbon degradation could occur in the absence of manure.

Optimum moisture content for a compost blend is ~50%, however some ingredients poorly absorb water and any water addition to the compost mixture should be sufficient to dampen the blend yet prevent clogging of the air spaces and generation of large volumes of leachate and run off.

When blending the organic amendments with the drill cuttings, the ratio is important. Our studies with Oxford clay, a highly reactive clay, suggested an optimum ratio of 1:1 to control the quantity of inorganic material present in the resulting compost and also to prevent clay hydration and compaction. If this occurs, oxygen supply to the compost blend will be reduced and will likely result in the formation of anaerobic pockets and decreased hydrocarbon degradation. The compost blend can be adjusted to minimize the likelihood of compaction by ensuring an optimum particle size distribution with an efficient mixing or turning regime to redistribute the ingredients and increase aeration. Drill cuttings from sandy or inert formations are unlikely to suffer these operational problems.

Drill cuttings created from salt formations may significantly affect the composting rate (not tested) and increase the conductivity of the end product but source segregation of drill cuttings from different sections and formation types is operationally difficult. It is likely that, unless a well is drilled where formation type is uniform, cuttings would be delivered to a composting operation as a blend of formation types.

The data has shown that as the hydrocarbon loading in the compost is increased, the longer the reaction time required. Tests showed that all the base fluids tested (from synthetic linear paraffins to diesel) will degrade to background levels within the typical life span of a mature compost pile.

The laboratory-scale box composters used for this study are appropriate to pilot scale any proposed composting blends when starting a new operation. They are easy to construct and easily maintained, with the temperature profile and the final TEH concentration only being required. Successful composting on this small scale will help identify any potential problems prior to large scale use.

Consequences for Drilling Operations – Specific requirements for the formulation of the drilling fluid to ensure efficient composting reaction will impact the applicability of this technology as a remediation technique. Many different oil- or synthetic-based drilling fluids are in use globally, and the suitability of changes to the fluid formulation required will depend on the technical performance of the fluid required, the logistics of supplying the necessary ingredients and the cost: benefit ratio. As such, a holistic approach is required.

The data presented in this paper has suggested that for a fast and efficient composting reaction the most suitable continuous phase would be a synthetic hydrocarbon (LP or LAO), yet as composts are required to mature prior to sale or use, all base fluids would ultimately be degraded to acceptable limits. Specifics of the composting operation, time constraints and throughput requirements may exclude the use of composting for the harder to degrade base fluids (*e.g.* diesel) but theoretically all can be treated.

It has been shown that the choice of drilling fluid internal phase salt has little impact of the efficiency of hydrocarbon degradation and as the conductivity of the end product was within most regulatory limits[4] changing from the standard calcium chloride internal phase is not necessary for the technique to be used, but may be necessary if specific regional/state environmental legislation dictates. The advantage of using formate or acetate salts is that these have the possibility of degrading during the reaction. Salts containing a nitrogen component may also add beneficial nutrients to the end product. Drilling fluids containing these salts types can be produced that have equivalent technical performance to the calcium chloride systems, although these salts may impact the cost and other aspects of the drilling operation.

Salt (sodium chloride) that enters the drilling fluid during drilling was shown to have little impact on the composting efficiency, probably due to the low concentration present. It is postulated that this would be the case with all salt types, unless specific compost regulations for that area control the quantity of the specific cations or anions. Laboratory scale tests and evaluation of the end product can form part of a quality control procedure if necessary.

Weighting materials used in the drilling fluid again had little impact on the efficiency of the composting reaction. Ultimate choice would depend on the specific legislation regarding the permitted heavy metal content of the end product. This varies considerable between locations and therefore choice would have to be on a case-by-case basis. Barite, hematite and ilmenite have all been used successfully in drilling fluids around the world. Hematite and ilmenite are much harder minerals than barite and if used, must be ground to a finer size than the standard API barite to reduce drill bit wear. The availability and location of hematite and ilmenite mines will also impact the decision to use these minerals in certain areas.

Nomenclature

Aerobic = *Requiring oxygen.*
Anaerobic = *Not requiring oxygen. Oxygen is often toxic to these processes.*
Actinomycetes = *A large and complex group of bacteria which among other characteristics have a mycelial growth phase.*
Diesel = *Non-specific collections of hydrocarbon compounds, generally having a high aromatic (>25%) and high PAH (>0.35%) contents.*
EMO = *Enhanced Mineral Oil - much lower aromatic content than diesel (<0.5% aromatics, <0.001% PAH) and contain cyclic hydrocarbons and branched paraffins.*
Humus *Organic matter that has decayed to a relatively stable, amorphous state.*
LAO = *Linear Alpha Olefin – Synthetic base fluid of aliphatic hydrocarbons, no aromatics, no cyclic hydrocarbons, no branched paraffins, unsaturated.*
Lignin = *A rigid polymer derived from 2 amino acids - phenylalanine and tyrosine. The structure of lignin is complex. In plants it is used for example, to provide rigidity and waterproofing to plant structures.*
LP = *Linear Paraffin – Synthetic base fluid of aliphatic hydrocarbons, no aromatics, no cyclic hydrocarbons, no branched paraffins, fully saturated.*
LTMO = *Low-Toxicity Mineral Oil - reduced aromatic content compared to diesel (0.5-5% aromatics and 0.001-0.35% PAH).*
Mesophiles = *Bacteria that optimally grow in a temperature range of 20-40°C.*
Mycelia = *A collection of long, branched thread-like growths. Particularly present in fungi and certain bacteria.*
PAH = *Polycyclic aromatic hydrocarbon*
PCB= *Polychlorinated Biphenyl*
TEH = *Total Extractable Hydrocarbons using a solvent extraction method, and as measured by GC-FID.*
Thermophiles = *Bacteria that optimally grow in a temperature range of >40°C.*

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Table 1 – Optimum Composting Parameters

Parameter	Optimum
C:N Ratio	25:1 – 30:1
Particle Size	Agitated systems – 12.5mm Natural Aeration – 50mm
Moisture Content	50-60%
Temperature	55°C
Agitation	None – periodic turning in simple systems Short bursts of agitation in mechanized systems
Heap Size	Varies as need to avoid overheating and type of system

Table 2 – Electrical Conductivity Data for Composts Prepared with Different Internal Phase Salts

Sample	Electrical Conductivity (dS/m)
Calcium chloride	12
Calcium ammonium nitrate	11
Potassium formate	10
Potassium acetate	8
Calcium nitrate	7

Table 3 – Australia Compost Application Rates Based on Electrical Conductivity. WRAP[4]

Electrical Conductivity Range, dS/m	Maximum Application Rate, liter/m^2	
	Sensitive Plants	Tolerant Plants
0-1	Unlimited	Unlimited
1-2	<15	<60
2-4	<8	<32
4-8	<4	<16
8-12	<2.5	<10
>12	<2	<8

Table 4 – Heavy Metal Concentrations (analyzed by ICP-MS) for Weighting Agents.

Weighting Agent	Barite	Hematite	Ilmenite
As (mg/kg)	8.38	1.61	<0.3
Cd (mg/kg)	0.98	0.1	<0.009
Cr (mg/kg)	7.97	56.63	206.2
Cu (mg/kg)	26.32	10.46	17.92
Ni (mg/kg)	8.78	3.96	40.75
Pb (mg/kg)	443.1	33.03	0.79
Se (mg/kg)	0.35	<0.09	<0.09
Zn (mg/kg)	951.2	17.64	15.67
Hg (μg/kg)	7815	296.8	13.1

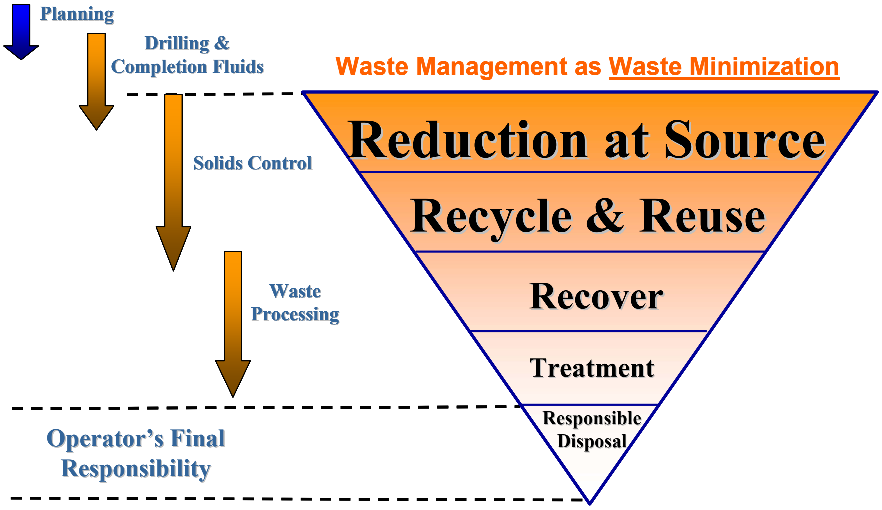

Figure 1 – Pollution Prevention Hierarchy

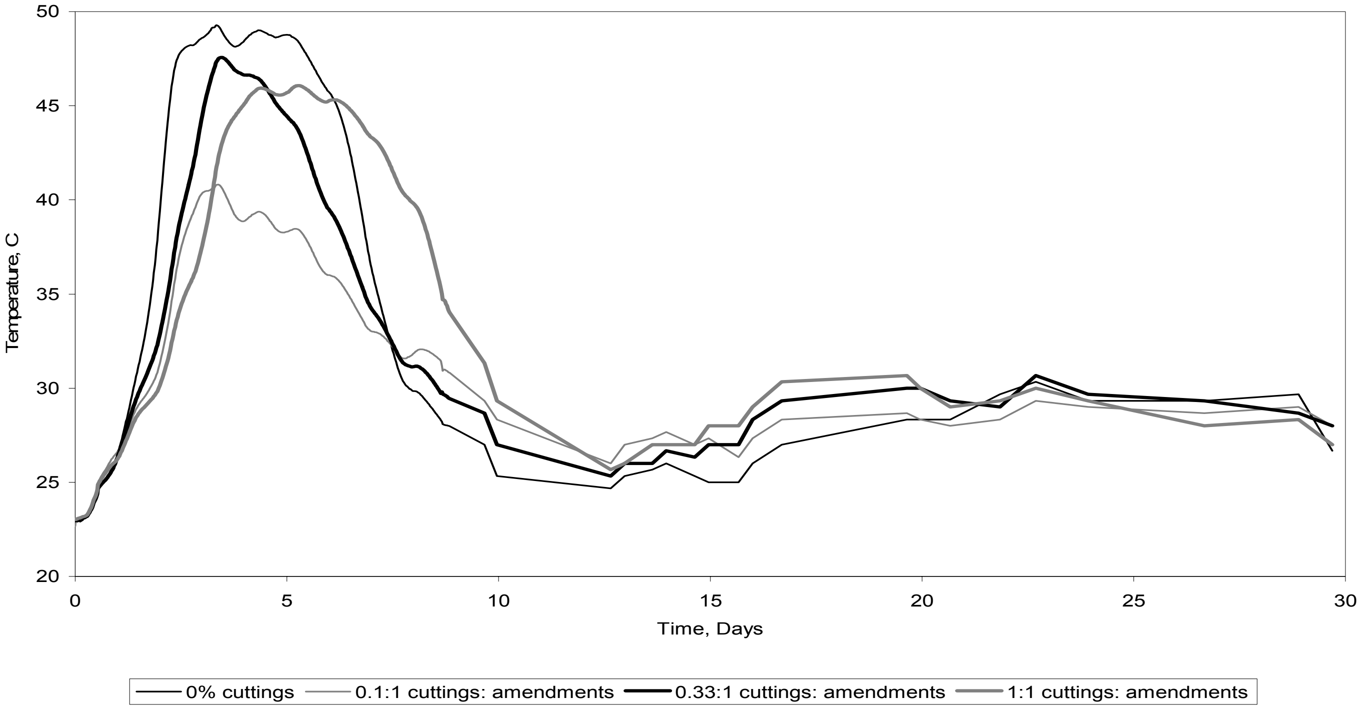

Figure 2 – Temperature Profile of Compost Prepared at Various Cuttings: Amendments Ratios (0-1:1)

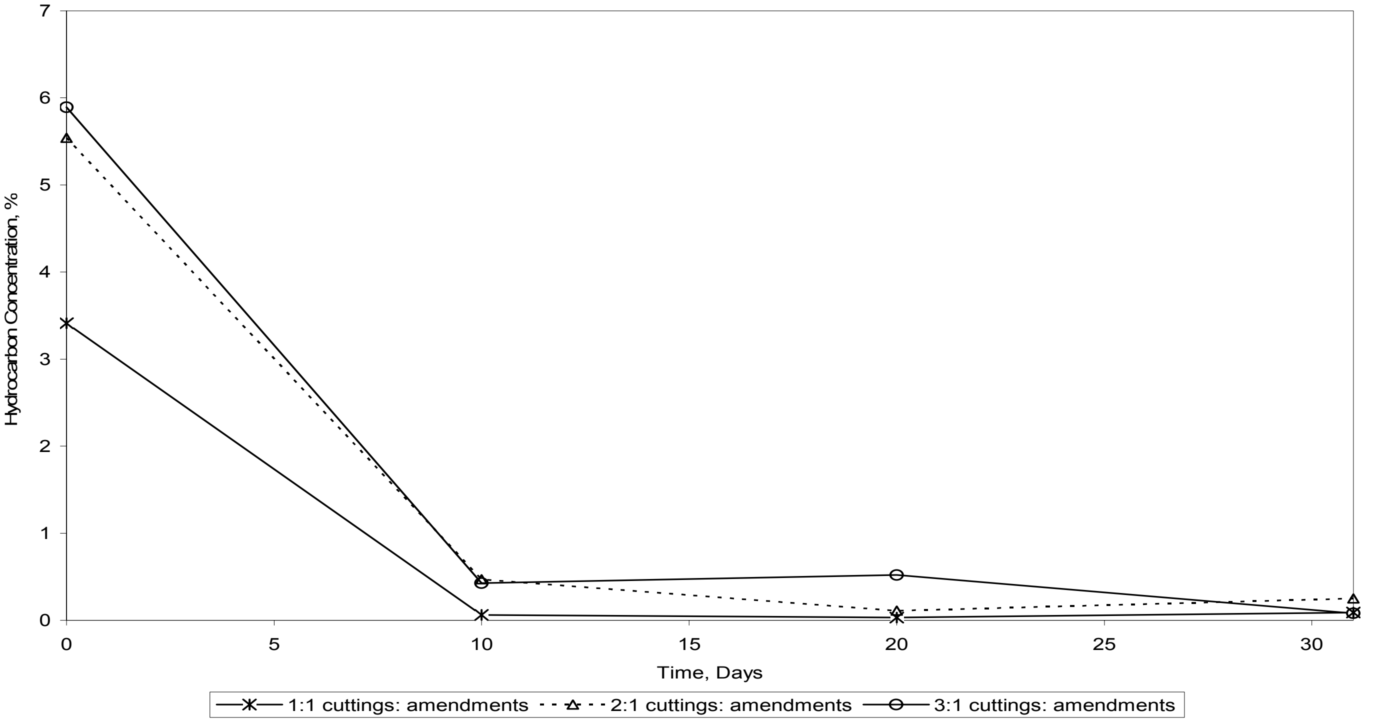

Figure 3 – TEH Content of Compost Prepared at Various Cuttings: Amendments Ratios (0 to 1:1)

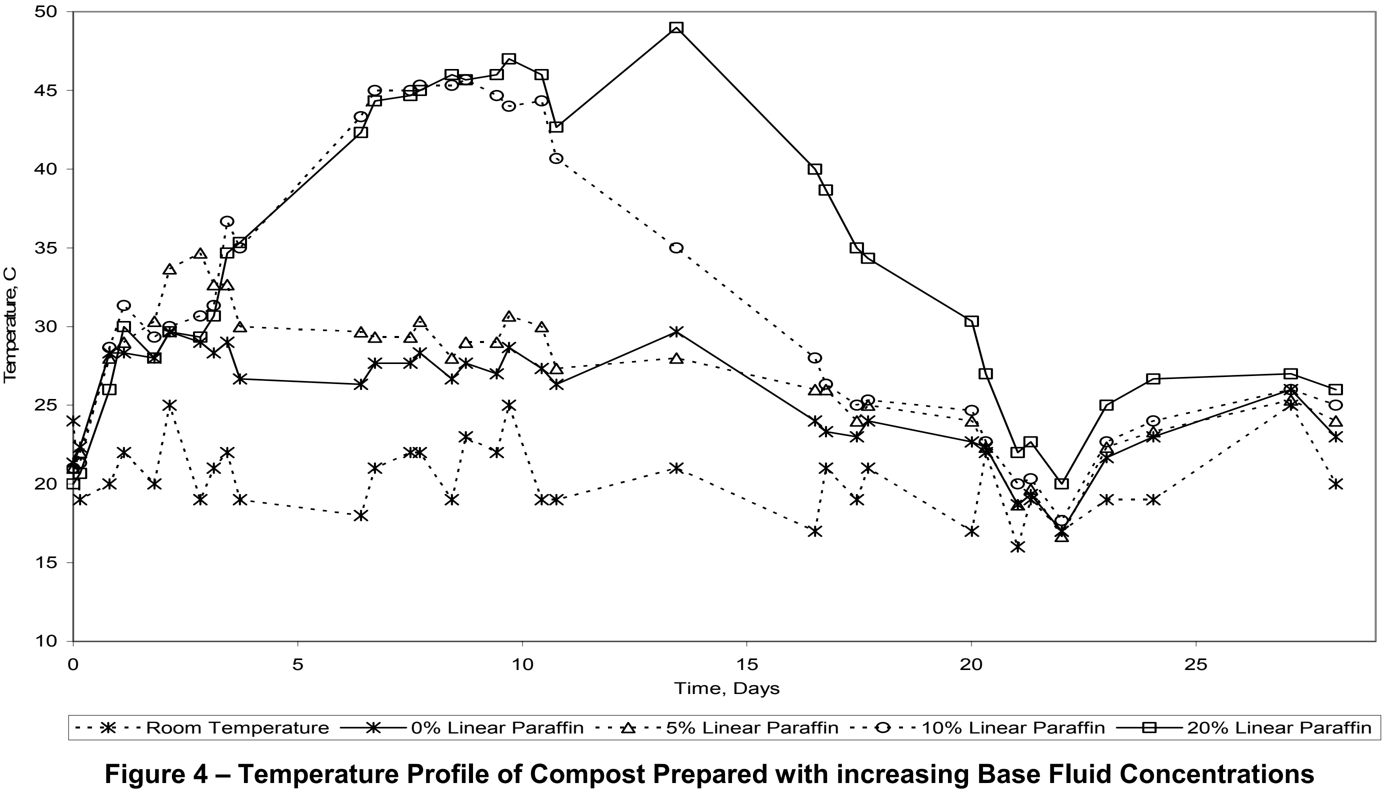

Figure 4 – Temperature Profile of Compost Prepared with increasing Base Fluid Concentrations

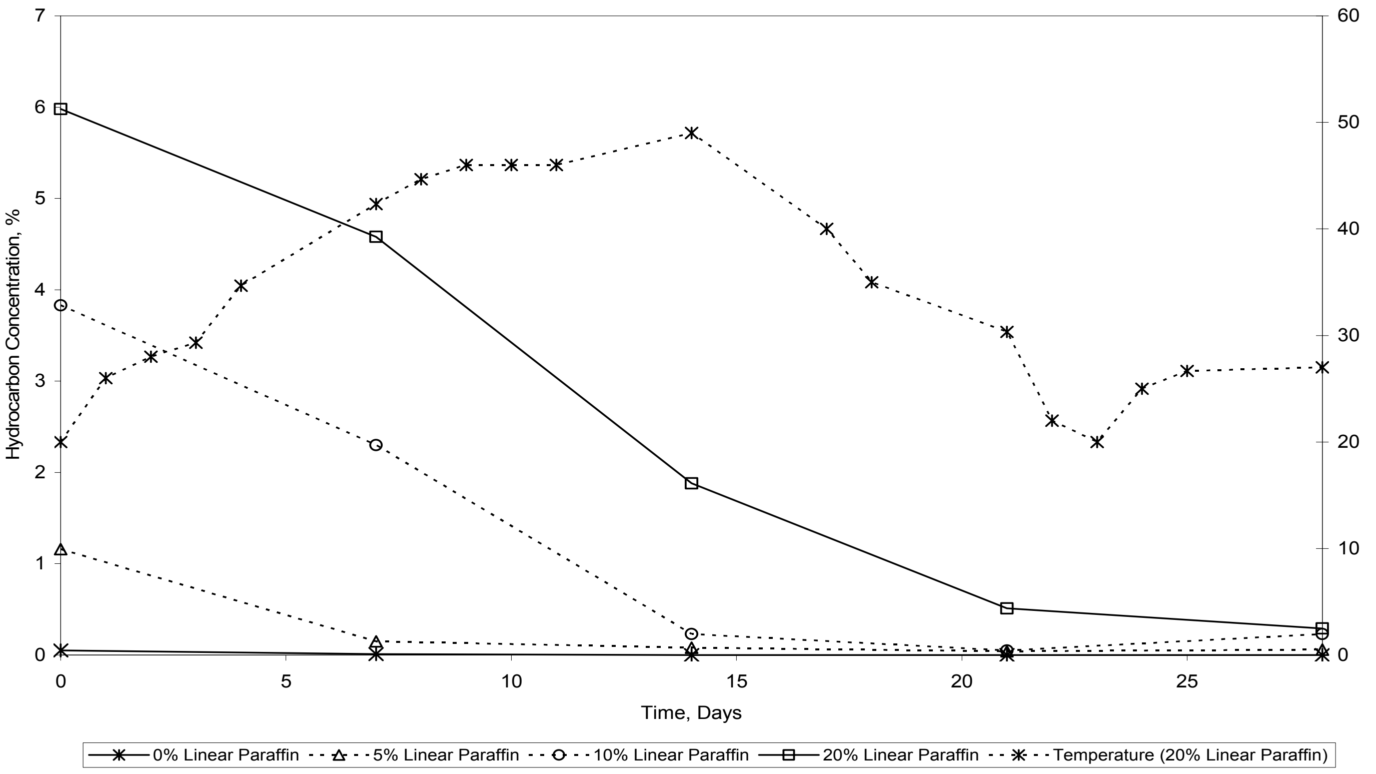

Figure 5 – TEH Content of Compost Prepared with increasing Base Fluid Concentrations

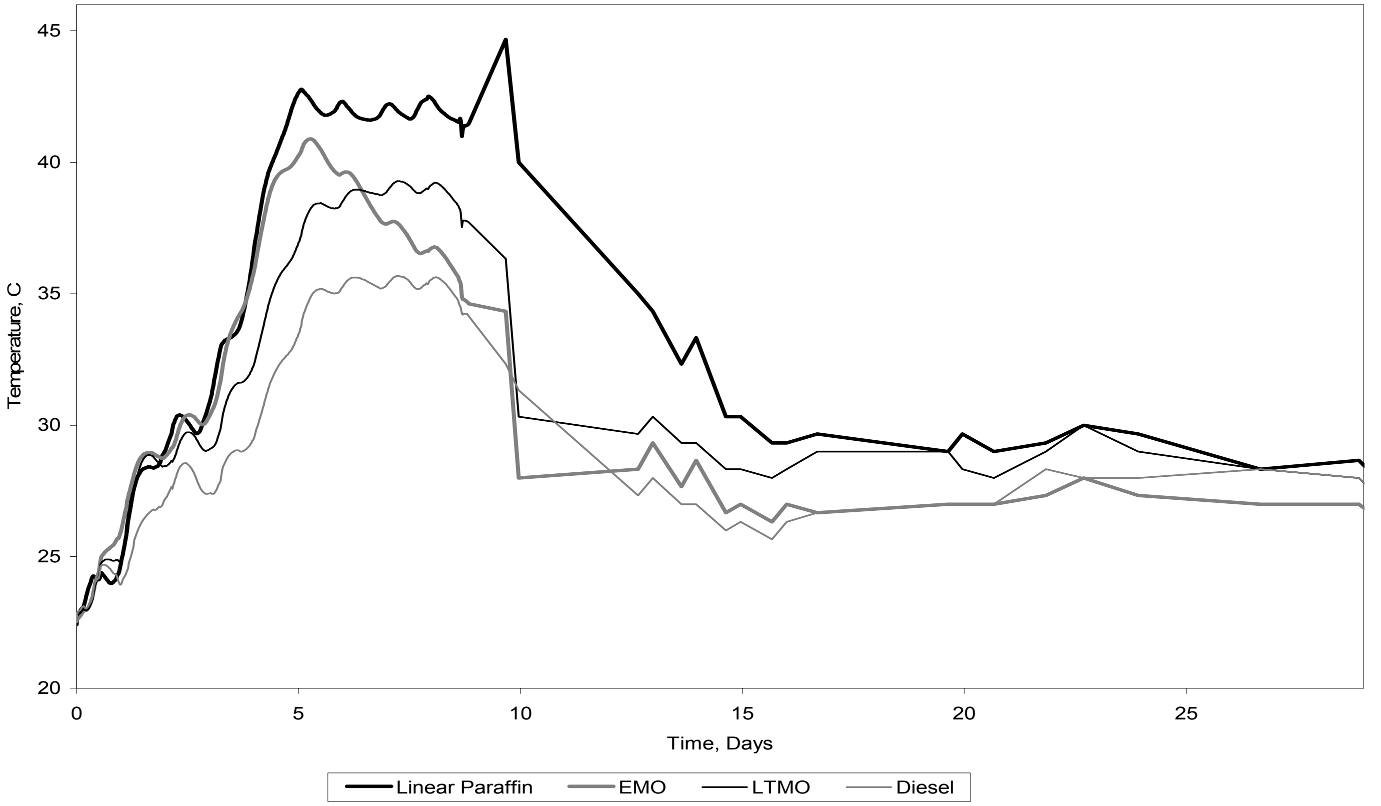

Figure 6 – Temperature Profile of Compost Prepared with Varying Base Fluid Types.

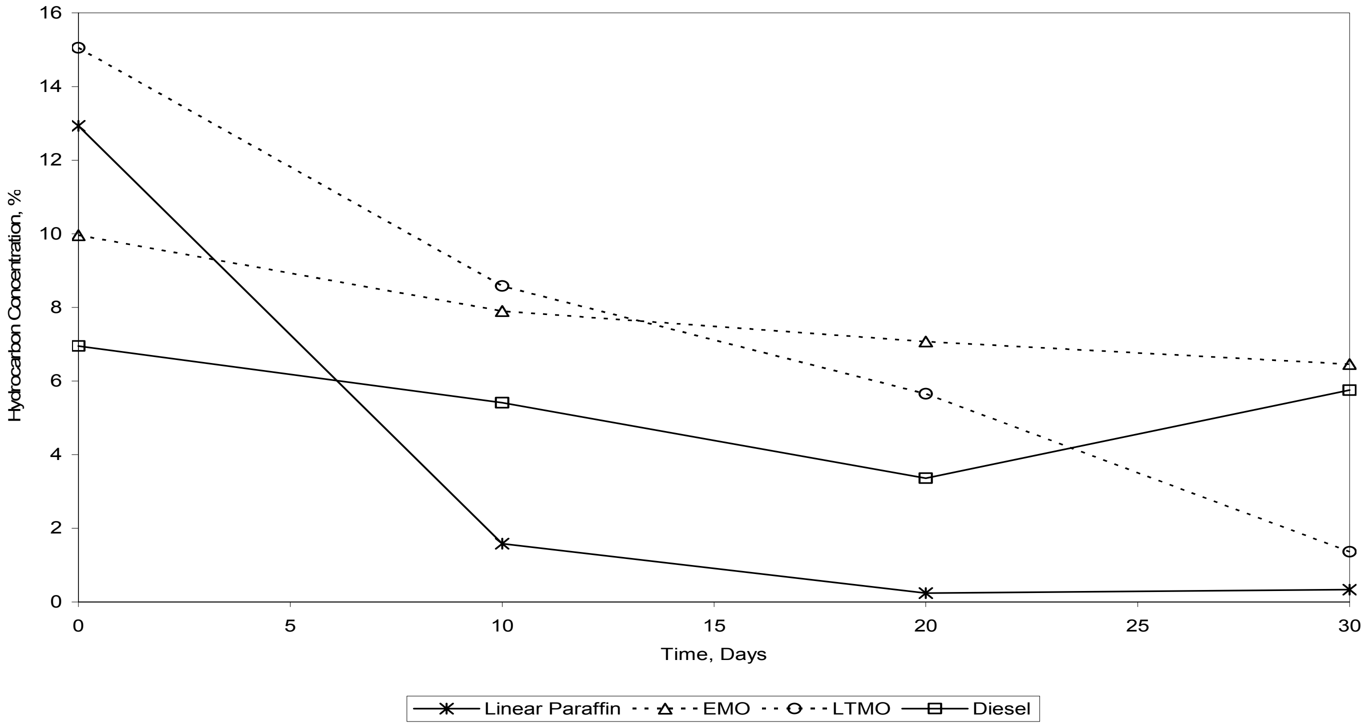

Figure 7 – TEH content of Compost Prepared with Varying Base Fluid Types.

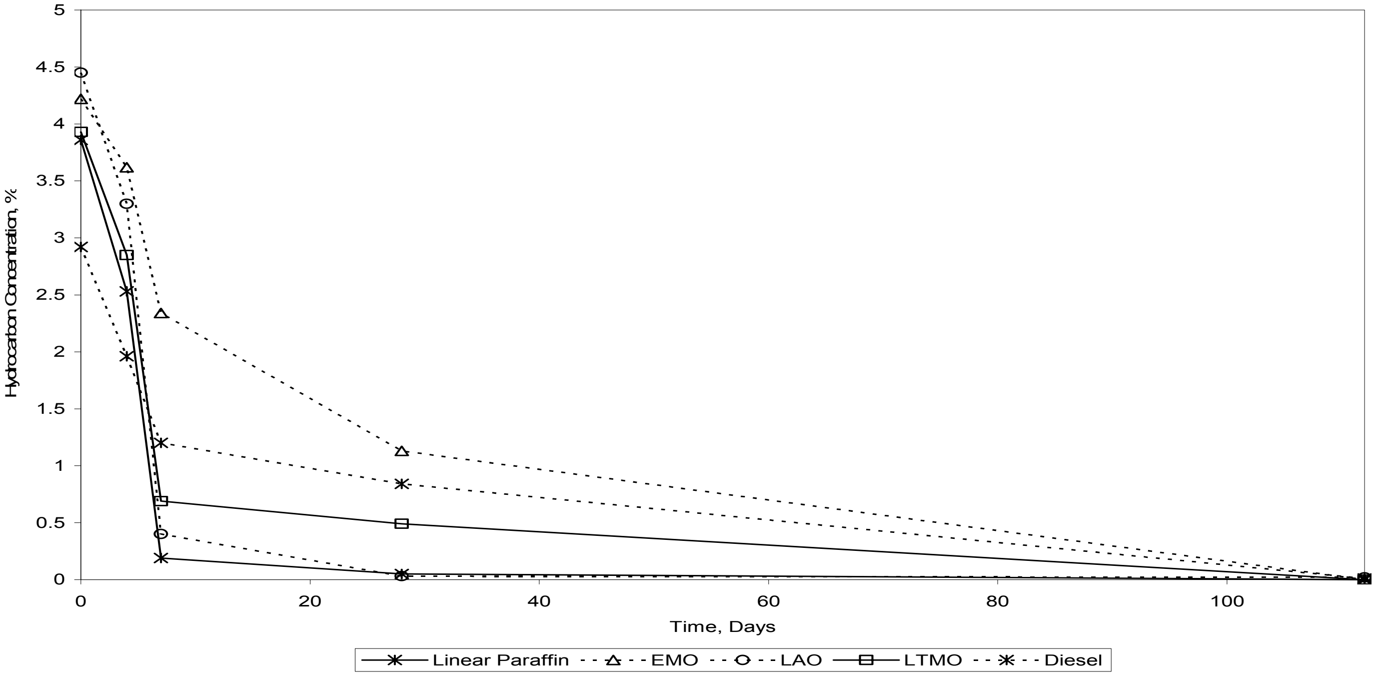

Figure 8 – TEH content of Compost Prepared with Varying Base Fluid Types.

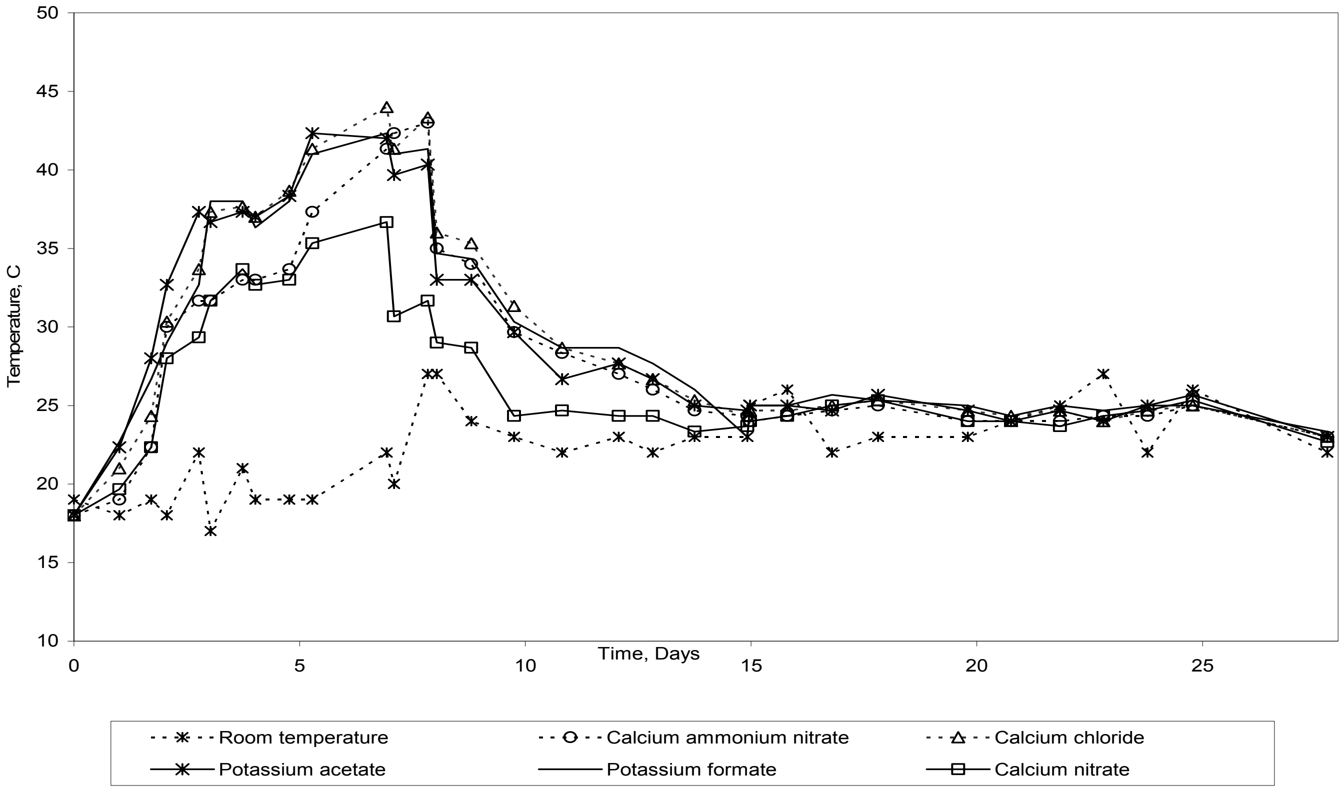

Figure 9– Temperature Profile of Compost Prepared with Varying Internal Phase Salts

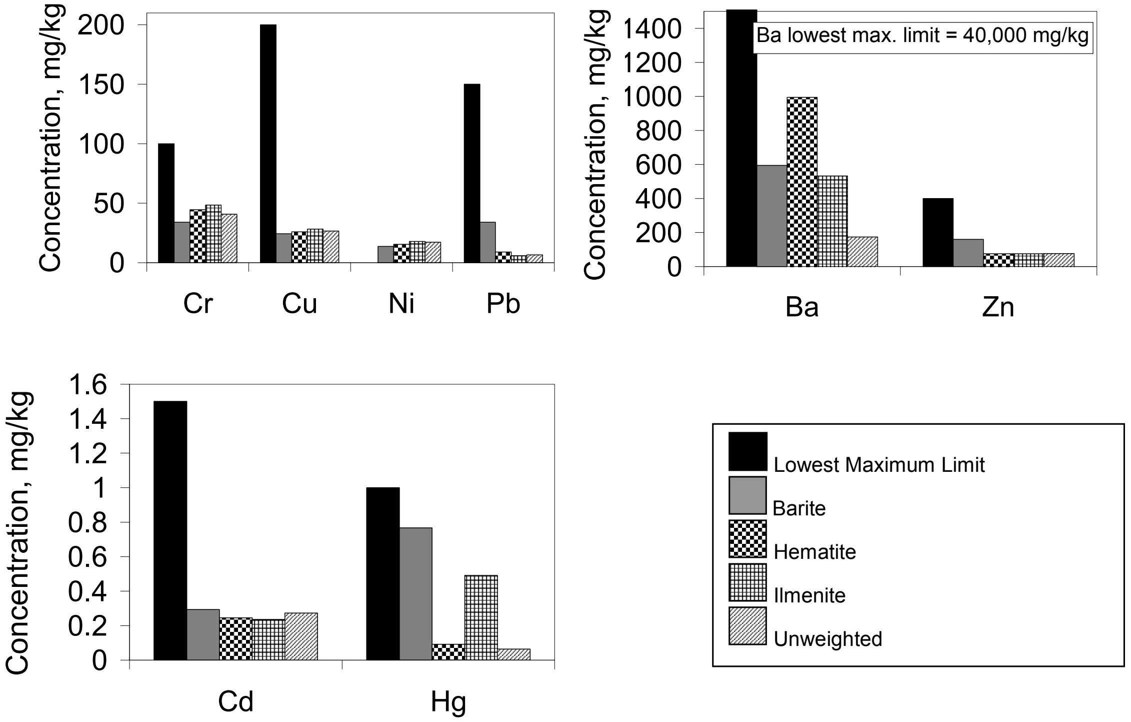

Figure 10 – Heavy Metals Analysis of Compost Prepared with Various Weighting Agents

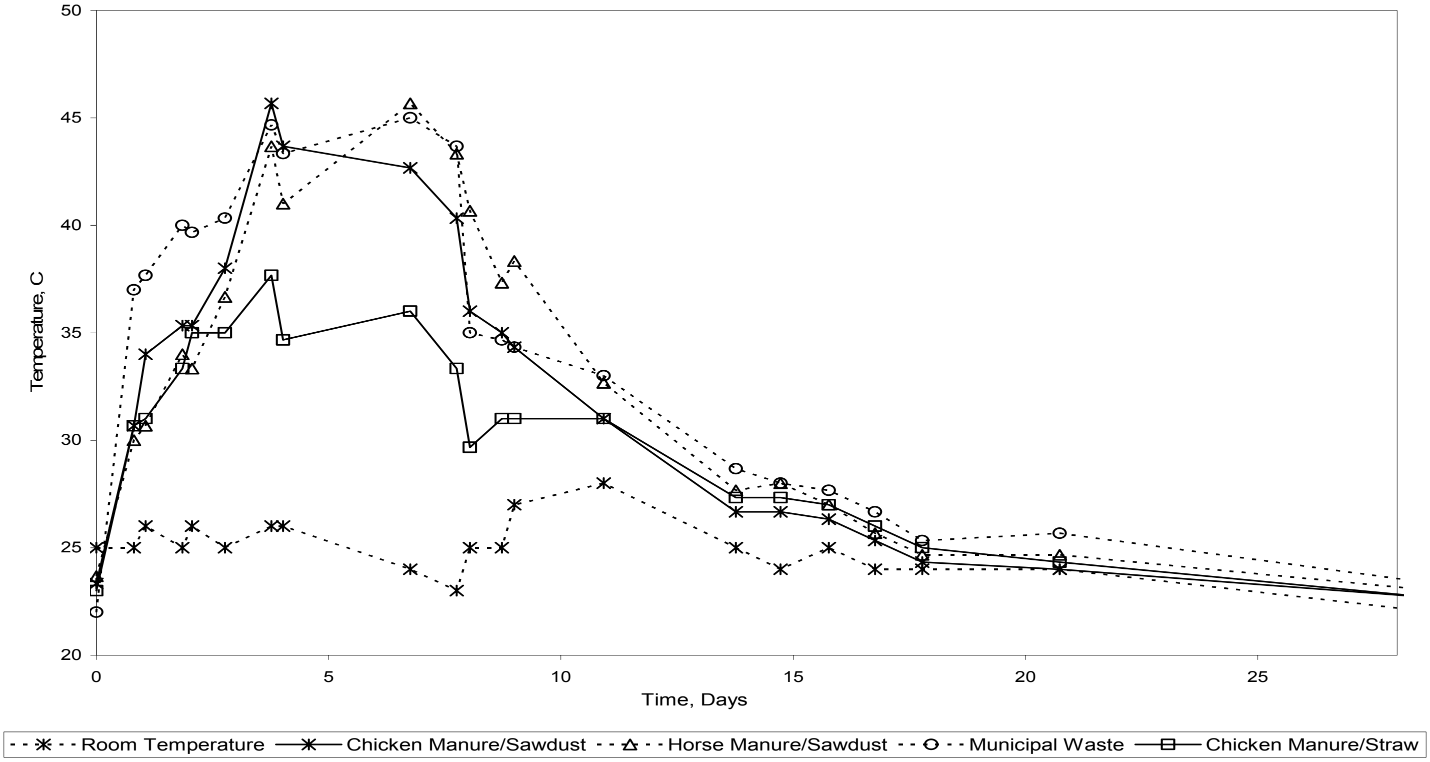

Figure 11 – Temperature Profile of Compost Prepared with Various Organic Amendments

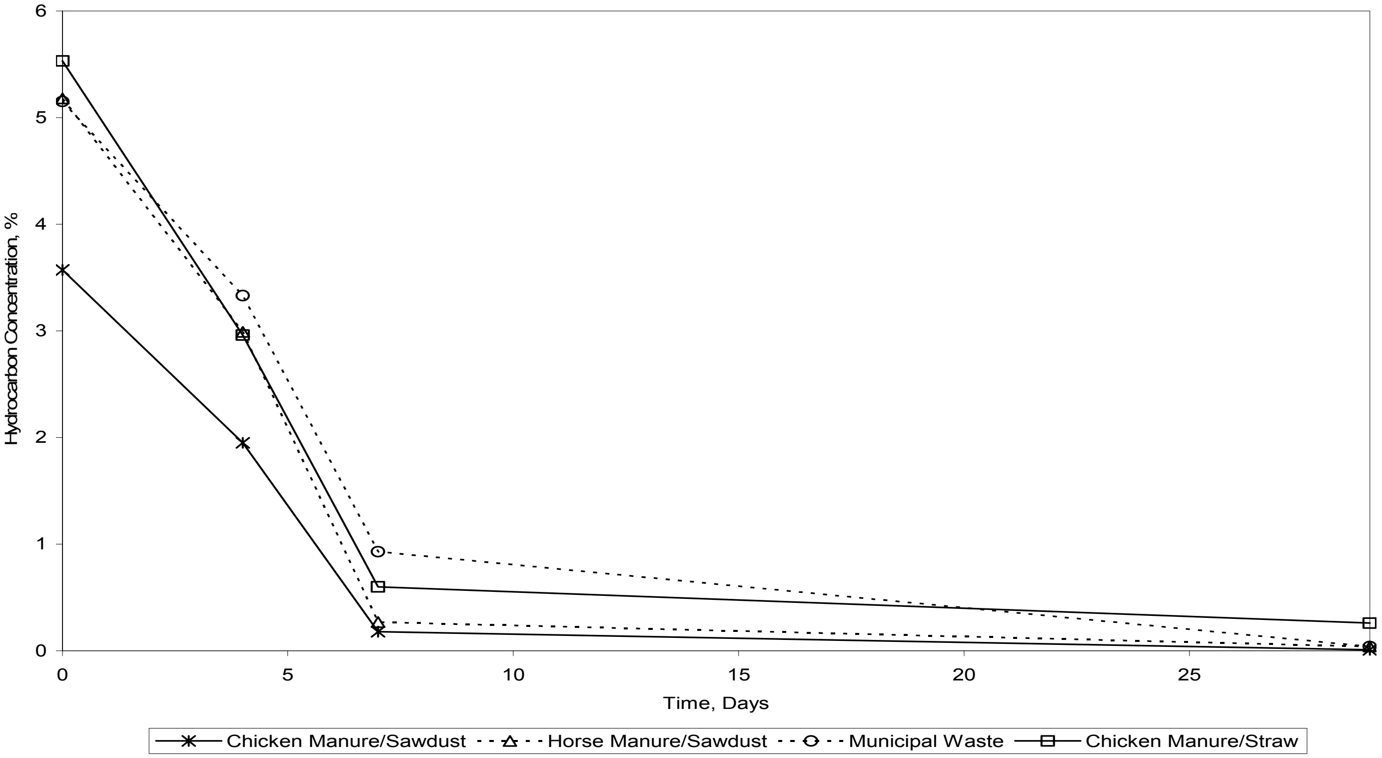

Figure 12 – TEH Content of Compost Prepared with Various Organic Amendments