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IS PRE-BIOLOGICAL TREATMENT OF ORGANIC WASTES THE BEST OPTION FOR RECYCLING ORGANIC MATTER TO SOIL?

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ABSTRACT

Recycling organic wastes to land is seen as a beneficial and sustainable use of such wastes as it improves soil structure, fertilizes the soil, conserves natural resources (N, P, K), and sequestrates organic carbon into soils that may help to off-set global warming. The requirement to divert biodegradable organic matter from landfills means that potentially much more organic waste may be recycled to land. The current trend is however to pre-biologically treat organic waste prior to recycling and this has some benefits such as reduction in odour producing potential and destruction of pathogens. Such processes however also lead to a more rapid return of the carbon to atmosphere as CO_2, and may consume energy for the biological treatment, and produce waste streams that require additional treatment. All these additional steps will result in more CO_2 emissions, and possibly emissions of other greenhouse gases such as nitrous oxide, and the loss of potentially valuable nutrients. Therefore the question is raised: is it better to pre-biologically treat organic wastes destined for recycling to land? This paper highlights some of the issues that may need to be considered in order to provide an answer.

KEY WORDS

Anaerobic digestion, biodegradable, carbon, compost, landfill diversion, methane, nitrous oxide, soil, waste

INTRODUCTION

Organic wastes are produced from a variety of sources such as agriculture, horticulture, forestry, industry, sewage treatment and households. These wastes are mainly derived from crops grown on land and contain elements, such as N, P, K, and S, originally found in the soil as nutrients. The major element of organic matter (C) is however derived from the CO_2 taken up by the plant from the atmosphere. The current trend is to recycle and reuse organic wastes as a resource, and their disposal in landfill is being actively discouraged [7,8,10,11]. Recycling organic wastes to land would benefit soil quality, sequestrate C into soils, return the nutrients removed from the soil in crop offtake, and help to establish a more sustainable use of soil and fertilizers.

Most organic wastes recycled to land are likely to be biologically pre-treated[11] by either composting or anaerobic digestion to give a "stabilised" product with a relatively low biodegradability. Biological treatments result in mineralization of part of the organic C to CO_2 and also additional CO_2 production from the consumption of energy and resources associated with their manufacture and operation, (although anaerobic digestion recovers some energy from the CH_4 produced). Biological pre-treatment of organic wastes may also release fertilizer elements such as N, P, K and S, which may be lost in process liquid and gaseous waste streams that also require treatment before disposal. Other elements such as toxic heavy metals (Hg, Cd, Pb, Cr) may concentrate in the biotreated waste making it less attractive as a soil amendment, i.e. the C (or nutrient N, P, K and S) to metal ratio may decrease.

If organic waste is recycled to land without pre-biological treatment then all its carbon and nutrients are also recycled to land, and the potential accumulation of heavy metals in soils is reduced as the nutrient to metal ratio is maximised. This might be considered as an optimal approach for sustainable soil management, and maximise the potential for C-sequestration to soil to reduce global warming. This simple view is affected by many other factors including, transport of waste to and from the land, emissions of pollutants from organic wastes added to land, and the need to sanitise organic wastes from risks of pathogen transmission [6,18].

Biological pre-treatment of organic wastes prior to recycling to land is carried out for several reasons such as reductions in its mass and volume, biodegradability, odour producing potential, and pathogen contents. The addition of "raw" un-stabilized organic wastes, such as some paper waste sludges, abattoir wastes (blood and guts) and plant (clover in organic farming) crops, to soils has however been widely practiced [17]. Therefore there is some acceptance of using raw un-stabilised readily biodegradable wastes for soil organic amendment.

This paper considers whether it is better overall to pre-biologically treat or not organic waste destined for recycling to land. To answer this question requires a full life cycle analysis of a complex system that may include factors that have not previously been considered in this context. The paper, however, does not claim to provide this answer but seeks to highlight some of the less obvious factors that may need to be considered in order to give a sound scientifically based answer.

WHY PRE-BIOLOGICAL TREATMENT OF ORGANIC WASTES?

There are several reasons for pre-biologically treating organic wastes prior to their disposal, many of which are familiar to the water industry and include:-

- Reduction in malodour production;
- Sanitation of waste by destruction of pathogens;
- Reduction in waste mass (this reduces volumes for transport and final disposal reducing environmental emissions of CO_2, NO_x and SO_2 from vehicles);
- Energy recovery from anaerobic digestion (from combustion of CH_4 as a biofuel);
- Microbial decomposition of toxic organic compounds present in the waste; and
- Biostabilisation of the waste prior to landspreading (this reduces the potential impact on the soil if the waste decomposes rapidly, e.g. temporary development of anoxic conditions with associated odour, methane production, and soil acidity).

WHAT IS BIOLOGICAL TREATMENT?

Organic waste biological treatment is either aerobic composting or anaerobic (methanogenic) digestion of the waste by micro-organisms. The organic carbon (OC) of the waste is mineralized (by oxidative reactions) to CO_2 by the loss of electrons from the OC, which are passed to an electron acceptor (that is reduced). These reactions release energy, some of which the microbe uses for growth i.e. the synthesis of new microbial biomass from some of the organic waste carbon.

AEROBIC COMPOSTING

Under aerobic composting conditions, O_2 is the electron acceptor and the process is analogous to burning the waste and can be considered as a form of combustion (bio-combustion). Composting is usually carried out at thermophilic temperatures (50-70^oC) achieved naturally by the heat generated by the microbial bio-combustion process. These high temperatures will kill most faecal pathogens sanitizing the waste.

ANAEROBIC DIGESTION

In anaerobic (methanogenic) digestion, O_2 is absent and some of the CO_2 produced from the oxidation of the waste is used as the electron acceptor and is reduced to methane (CH_4), thereby producing a mixture of CO_2 and CH_4 (biogas) from the organic waste. The combustion of CH_4 for energy generation results in the overall conversion of waste OC to CO_2. Anaerobic digestion is typically carried out at mesophilic temperatures (30-40^oC) and therefore sanitation of pathogens is less achievable than with composting although thermophilic anaerobic digestion is possible.

MICROBIAL GROWTH DURING DECOMPOSITION OF ORGANIC WASTE

During organic waste decomposition, as some of the waste C is used for microbial growth, there is a transformation of one form of organic matter (the original waste) into another (microbial biomass). This microbial biomass will also subsequently die off and slowly decompose contributing to a further overall loss in OC. The amount of microbial biomass formed is linked to the amount of energy released during decomposition and generally aerobic degradation produces more energy than anaerobic degradation and therefore more microbial growth. Typically about 40% and 10% of the decomposed carbon may be converted to microbial biomass during aerobic composting and anaerobic digestion respectively.

FATE OF OTHER ELEMENTS IN WASTE DURING BIOTREATMENT

Nitrogen

Most organic wastes contain organic nitrogen (ON) in compounds such as proteins, amino acids, and nucleic acids. During decomposition ON is mineralized to ammoniacal-N (NH_4^+) and some of this may be lost in aqueous process waste streams or released to the atmosphere by volatilization as ammonia

(NH_3) from gaseous waste streams. Ammonia pollution of water and air is of concern and the UK is committed to reducing NH_3 gaseous and aqueous emissions [5]. During organic waste decomposition some of the released NH_4^+ will be used as a nitrogen source for microbial growth and be converted microbial organic N. The overall amount of N mineralised is therefore dependent on the N content of the waste degraded, which can be considered in terms of its C/N ratio, and the amount of new microbial biomass formed. If the C/N ratio is high (<20) then during composting most of the N should be required for microbial growth and little if any immediately released.

Composting however is notable for volatile NH_3 emissions driven by the high temperature and aeration if present. It is considered valid to estimate the N losses from the possible future UK composting of biodegradable waste diverted from landfilling in the context of UK emissions, a scenario for which the following assumptions are made:

- composting rises to 5 million tonnes of organic waste dry matter (DM) per annum;
- N content is 2.0% of the DM;
- composting reduces the waste DM by 50%; and
- the final N content is still 2%.

On this basis, 50,000 t N/a may be lost. If released as gaseous NH_3 this is about 15% of the current UK NH_3 emissions and would compromise targets for reducing NH_3 emissions. Additionally 50,000 t N/a represents ~3% of the UK agricultural nitrogen fertilizer requirement [2] of 1,624,500 t N/a.

Under aerobic conditions NH_4^+ may be oxidized to nitrate by nitrifying bacteria (nitrification), which can be a pollutant of surface and ground waters. Nitrate and NH_4^+ limits in discharged effluents are decreasing and N removal is often required, and nitrate removal is often achieved by anoxic microbial denitrification. However the net effect is additional CO_2 emissions from energy consumption by the treatment processes, and the potential formation of some nitric oxide (NO) and nitrous oxide (N_2O) by the nitrifying and denitrifying microbes [13,23].

During aerobic composting nitrification and possibly denitrification activity might lead to significant N_2O emissions of 0.33-0.47 g N/kg DM for some wastes [3] (about 1% of waste N content). Also if gaseous emissions are treated in biofilters or bioscrubbers, NH_3 lost by volatilization during composting may form N_2O from nitrification and denitrification in the biological gas treatment systems. If gas treatment is by chemical scrubbing then there may be an N rich effluent that also requires treatment before disposal.

With anaerobic digestion of organic wastes there is usually a net mineralization of organic N to NH_4^+ most of which will be found in the aqueous phase. Typically the digester sludge may be de-watered and the NH_4^+ rich liquor generated will require treatment, which if by the nitrification and denitrification process, results in N_2O emissions. Composting may also sometimes produce leachates rich in NH_4^+ that require similar treatment.

Therefore losses of N from biological pre-treatments may occur in both aerobic and anaerobic processes and these represent significant environmental emissions that when treated by nitrification and denitrification may also generate the more potent greenhouse gas N_2O.

Phosphorous and heavy metals

Most heavy metals (e.g. Hg, Pb, Cr, Cd, Zn, Ni and Cu), and phosphorous (as phosphates) are not very soluble and most will remain with and be concentrated in the organic matter during biotreatment. Some losses may occur from liquid effluents that may potentially require further treatment. Phosphorous is an important agricultural fertilizer and pollutant of surface waters, and is present in organic matter in many organic compounds, e.g. nucleic acid, and as inorganic phosphates. Soil P additions in the UK from manure (200,000 t/a) and inorganic fertilizers (150,000 t/a) exceed crop offtakes by about 120,000 t/a and soil P concentrations are in excess [26]. Therefore there is scope for reducing inorganic phosphate fertilizer use by recycling more organic wastes to land but the potential may be limited if the P in the organic wastes is concentrated. Digested sewage sludges are generally rich in P and this may be used to limit their application rates [9]. Heavy metal accumulation in soils is an area of concern but as some metals are also important as nutrients [12] thoughtful consideration of the heavy metal addition in soils is required, including the impact of recycling raw wastes with lower metal contents compared with pre-biologically treated wastes.

Potassium, magnesium and sulphate

Potassium is present in organic wastes mostly associated within the cells of the plant, animal and microbial materials present in the organic waste, i.e. organisms usually take up K into cells as part of their osmo-regulation activity. During decomposition of intact cells they may lyse and K is then released from the cells and is found in the waste moisture. During composting this may be conserved if there is no leachate produced but in anaerobic digestion the K may be lost in the liquors. Typically anaerobically digested sewage sludges have low K contents relative to N with respect to plant nutrition. In the UK, soil K contents are in excess of crop requirements but there is widespread use of inorganic K fertilizers (about 420,000 t K/a) [2], and therefore appropriate recycling of organic wastes to land could reduce inorganic K fertilizer use.

Magnesium is similar to potassium in that it is an important nutrient and some may be lost in liquid effluents during biological treatment of organic wastes. It can however form insoluble salts with carbonates and phosphates and therefore some Mg may be retained as inorganic salts within the solids.

Sulphur as sulphate is an important plant nutrient and is often added as a soil fertilizer, particularly for grass, oil seed rape and cereal crops, as deposition from air has decreased significantly [2]. Sulphate is reduced by microbes under anoxic conditions to sulphide, which significantly contributes to malodours associated with decomposing organic matter e.g from anaerobic digestion. Sulphur is present in proteins and during anaerobic digestion of organic waste, this may form H_2S or other malodorous organic sulphur compounds, e.g. methyl sulphide, dimethylsulphide and dimethyldisulphide. Sulphur may be lost from biological treatment processes in aqueous effluents as sulphate and sulphides, and as H_2S in gaseous effluents. During composting, unless there is a significant leachate formation, most S will remain and be concentrated in the waste.

SUMMARY OF BIOLOGICAL TREATMENTS

Biological treatment processes have several distinct benefits though they also have features that may contribute to additional CO_2, NO, N_2O, and NH_3 emissions. Additionally there may be losses of K, Mg, P and S, which could replace the use of inorganic fertilizers, and anaerobic digestion has the potential to enhance the production of malodours.

RECYCLING ORGANIC WASTES TO LAND

BENEFITS OF RECYCLING ORGANIC WASTES TO LAND

The benefits of recycling organic matter to land are well understood and include:

- Enhanced soil structure;
- Better water holding capacity;
- Carbon sequestration;
- Recycling nutrients (N, P, K, S, metals);
- Maintaining soil biodiversity;
- Reducing soil erosion; and
- Conserving other natural resources.

However if this is considered in terms of the difference between recycling raw and pre-biologically treated wastes then some additional factors may need to be taken into account. Pre-biological treatment of wastes affects the chemical and biological properties of the waste and has entailed the use of processes that consume resources, produce emissions and result in losses of elements with fertilizer value. Additionally the fertilizer value of biologically treated waste is often poorer because remaining elements such as N are often in a stable unavailable form and are not released at rates that match plant growth requirements. Composted organic wastes are often viewed as soil conditioners rather than fertilizer sources. Recycling raw wastes to land may retain more of the fertilizer value of the wastes as they will be less biologically stable and will decompose more in soils releasing and making the nutrients available to the plants. However raw wastes have other dis-benefits when compared with pre-treated wastes.

EMISSIONS FROM WASTE TRANSPORT

Transport costs and environmental emissions are linked mainly to the volume and mass of waste transported. Organic wastes contain significant amounts of moisture and sometimes air and volume reduction from water and organic matter mass loss by pre-treatment seems sensible. Transport is also linked to application rates which may be lower if the waste has a higher fertilizer value and the raw waste substitutes for conventional inorganic fertilizers. The issue of environmental impacts from transport is complex and depends on the form of the organic waste and would need consideration on a case-by-case basis.

CARBON SEQUESTRATION IN SOILS

Carbon sequestration into soils by different management techniques including recycling organic wastes may have the potential to mitigate some of the increase in atmospheric CO_2 concentrations [21]. If raw rather than pre-biologically treated organic wastes are applied to land then clearly we might expect greater decomposition and CO_2 production in the soil from an equivalent amount of organic C applied. This is because the raw waste contains a high fraction of readily biodegradable organic matter that is rapidly degraded in soils whilst this fraction has already been removed in pre-biologically treated wastes. In the study by Reddy *et al* (1980) [15] waste decomposition was modelled by assuming wastes contained different fractions of readily, slowly and very poorly degradable organic matter. The fraction of readily degradable waste present in a wide variety of animal and plant wastes varied between 9 and 75% and the half-life for degradation of the very slow degradable fractions was also very long (ranging from 71 to 2,300 years). Therefore answering the question of whether adding raw or pre-biologically treated organic matter to soil results overall in more or less organic C sequestration into soils may be difficult as the losses during pre-treatment need to be taken into account and the slow decomposition of the residual recalcitrant waste fraction may take a long time.

PLANT NUTRIENTS

A key factor when adding fertilizers to land is understanding how nutrients behave in soil and become available for crops. With inorganic fertilizers all the nutrients are immediately bioavailable and any excess (not taken up by the growing crops) may present a risk of environmental emissions or be transformed by soil microbes. With organic fertilizers the bioavailability of nutrients may depend on the decomposition of the organic waste in soil. This is particularly important when considering N fertilizers.

NITROGEN FATE IN SOIL

The fate of excess N in soils from fertilizer applications is a key concern environmentally. Emissions to air include NH_3 from volatilization during application, and NO and N_2O from the microbial nitrification and denitrification reactions. Soils are a major source of global N_2O emissions and this is largely associated with inorganic N fertilizer application. About 0.25 - 2.25% of the N fertilizer applied may be emitted as N_2O accounting for nearly half of the soil N_2O emissions [20]. The controlled slower release of N from organic fertilizers may reduce such emissions if the organic fertilizer is applied to match crop growth. Organic N in stabilised composted wastes is however usually released too slowly to be an effective N source for crop growth. Adding raw organic wastes usually results in the release of mineral N as the waste decomposes that may better match the N requirements of the growing crop and minimise the environmental risks from excess mineral N in soil. If crop residues are ploughed back into soil and allowed to decompose with no crop present there can be an increase in N_2O emissions as the soil may become more anoxic (stimulating more denitrification) as a result of the increased soil respiration and availability of more carbon sources for denitrification [20]. Therefore the application of organic wastes must be managed appropriately with crop planting.

Smith (2000) [22] has revised estimates of the CO_2-C mitigating potential of UK agricultural land when N_2O emissions are included and these may vary between a decrease of 10% and an increase of 30%. Clearly the situation is complex and the key question of whether applying raw wastes to land would enhance or reduce these emissions, compared with pre-biological treated wastes plus inorganic fertilizers, needs to consider many factors.

BIODIVERSITY

An aspect of adding pre-biologically treated wastes that has not attracted much attention is the impact of the microbes in the treated waste on the native soil microbes. Even moderate applications of treated wastes may add significant populations of “foreign” non-soil microbes to the soil. For example if composted organic matter is applied at 5 t DM/ha to a soil with a microbial biomass of 200 mg C/kg it can be estimated that this might inoculate the soil with 40 mg C/kg of live and active “foreign” microbes. This assumes the compost is 20% C of which 10% is microbial C. A 20% inoculum of foreign microbes may have significant consequences on the stability and activity of the resident soil microbes and the question is posed whether it is better in terms of soil microbial biodiversity to have the organic matter decomposed within the soil by the native soil microbes. This will invariably depend on the need to maintain or enhance ecological soil function, the change of which is driven microbially.

ALTERNATIVE NON-BIOLOGICAL TREATMENT METHODS

Whilst application of pathogen containing un-treated raw wastes is restricted there are several non-biological treatment methods available that provide sanitation and odour control that do not result in significant mineralization of the organic waste carbon, although they may affect its biodegradability.

LIMING

The need to sanitize sewage sludge for agricultural use has led to the re-emergence of liming as a treatment method. This involves mixing lime (CaO) with the sewage sludge, typically at dosing rates of at least 50 - 200 kg/t DM [1,19]. The lime dissolves forming calcium hydroxide $Ca(OH)_2$ which causes the pH to increase to ~ 12 and heat production. The organic matter is preserved and the limed sludge is widely used on agricultural land particularly on soils of low pH. Liming of soils is standard practice and about 1.8 million tpa of lime is added to UK soils [2] to increase soil pH. Combining some of this lime with organic matter seems a sensible approach where appropriate.

THERMAL TREATMENT

Pasteurisation is a heat treatment that involves heating to about 60-70^{o}C for around 30 minutes. Such a heat treatment is sufficient to kill most of the active microbial cells although it will not kill microbial spores. Most faecal organisms and pathogens would be significantly attenuated by pasteurisation and the process has been applied to the treatment of sewage sludge. The process may also partially hydrolyse the organic waste increasing its biodegradability [4].

The treatment of organic wastes at temperatures above 100^{o}C can provide virtually sterilization of the waste. Thermal drying of sewage sludges is widely applied and can significantly reduce faecal microbes [25]. This may also impact the biodegradability of the organic wastes.

SONICATION AND OZONE TREATMENTS

Treatment of organic wastes by sonication and/or ozone has been considered for improving its biodegradability in for example anaerobic digestion. These treatments can result in death and lysis of microbial cells providing some sanitation of the waste [14]. However cell lysis releases soluble low molecular compounds from intact cells and this will result in an increase in the initial biodegradability of the waste which may affect its behaviour in soil.

IRRADIATION

Irradiation is a good method for sterilizing food items, has been used to sanitize sewage sludges [16] and may be applicable to other organic wastes. The irradiation has been shown to have little effect on the carbon mineralization of sewage sludges in soil but may have affected the mineralization of N in some cases [24]. Irradiation might then provide sanitation with no or little change in the organic matter characteristics and biodegradability.

CONCLUSIONS

This paper has highlighted some of the issues associated with the options for the management of organic wastes in the context of their recycling to land. These issues are quite embracing and cover public acceptance, public health, soil microbiology, soil fertility, soil protection, global warming, gas emissions and the conservation of natural resources. Whilst the future may increase the utilization of organic waste as a resource for recycling to land there may be some scientific questions relating to the overall impact of biological pre-treatments on sustainability.

A full life cycle analysis might be carried out to cover all the aspects discussed in this paper to assess whether there is any justification to considering whether pre-biological treatment for all organic wastes is the only and best option for recycling organic wastes to land. Perhaps there are some valid and defensible alternative options using raw wastes that might prove to have less overall environmental impact and result in greater benefit to the soil.

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