CRITICAL EVALUATION OF COMPOSTING OPERATIONS AND FEEDSTOCK SUITABILITY

PHASE 1 – ODOUR ISSUES

Department of Environment and Science

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DEPARTMENT OF ENVIRONMENT AND SCIENCE

CRITICAL EVALUATION OF COMPOSTING OPERATIONS AND FEEDSTOCK SUITABILITY CRITICAL EVALUATION OF COMPOSTING OPERATIONS AND FEEDSTOCK SUITABILITY

Phase 1 Report – Odour Issues

Final Report

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APPENDICES

SUMMARY

Arcadis has been engaged by the Department of Environment and Science (DES) to undertake a critical assessment, review and evaluation of composting operations in Queensland with a focus on odour management, feedstock suitability, contamination risks and the regulation of these aspects by DES.

Composting in Queensland is a significant industry which in 2017-18 converted 1.4 million tonnes of organic residues and waste into beneficial products which generally improve soil health and quality. There are around 25 companies of varying scales whose primary business is composting plus a number of other companies and councils that engage in organics processing in various forms.

Without a successful composting industry, significantly more organic waste would be landfilled or otherwise disposed to land without processing, resulting in a range of environmental and social impacts including significant greenhouse gas emissions.

The role of composting in the broader waste management system is set to grow over the coming years as councils and businesses look for ways to divert more organic waste from landfill, particularly food waste. The draft Queensland Waste Strategy sets ambitious targets for recycling waste and reducing landfill which will only be achieved if more organics are recovered and directed to beneficial uses. The Waste Strategy focuses on building a circular economy in Queensland and the recovery of organic waste is already a major contributor to that.

However, composting also has a high potential to impact on local communities and the environment. DES has received a considerable number of complaints about odour nuisance from composting operations, particularly in the Swanbank area near Ipswich, but also near other composting operations. The Queensland Government has committed to reducing those impacts with a particular focus on addressing odour management issues and contamination of compost products, arising from the use of inappropriate feedstocks.

This study aims to improve the Department's understanding of composting processes and odour emissions from composting; best practice management of composting; the suitability of different materials as feedstocks in composting and requirements for improving regulation of the industry. This report presents the findings of Phase 1 which is particularly focused on issues of odour control at composting facilities in Queensland.

Overview of findings

The report starts with a description of composting processes and different system options, as well as discussion about key process control parameters to minimise odour formation and release. It is noted that:

- Odours will form during composting even under optimal conditions. Nevertheless, failure to maintain optimal conditions is highly likely to make matters worse and the nature and noxiousness of the odours will be worse under sub-optimal conditions.
- Understanding the relationships between food source (feedstock), environmental conditions (e.g. temperature, air and water) and metabolic activity (microbial species, diversity and activity) is critical to successful operation of a composting process, including how odours are generated and managed.
- Getting the physicochemical composition of the feedstock mix right (i.e. optimal physical characteristics such as particle size and porosity plus optimal ratios of carbon, nitrogen and other nutrients) is the key to maintaining the consistent aerobic conditions necessary for low odour emissions, regardless of the composting system employed.

Composting Methods

The vast majority of organic wastes recovered in Queensland and processed through open window composting facilities. Turning of the windows is an essential part of the process in these systems and there are different approaches, noting:

- Turning frequency has less impact on the composting process than other key process variables such as feedstock physicochemical characteristics, moisture content and windrow size; but it can influence such things as the rate of decomposition, compost bulk density and porosity, and the time required to reach maturation.
- Turning a windrow in itself, has limited direct effect on maintaining aerobic conditions. Studies have shown that any oxygen which is introduced into a windrow during turning is generally consumed within hours.
- As such, the porosity of the composting materials is far more important, because it determines how freely fresh air can move through the pile. A degree of turning can help to improve porosity by loosening the materials and redistributing moisture. The use of bulking agents such as green waste or wood chips at appropriate particle sizes and ratios, is critical to maintaining porosity and air flow in passively aerated windrows.
- On the other hand, care must be taken not to overwork or excessively turn a windrow. An aggressive turning schedule or method can reduce the porosity of a windrow by breaking down compost particles, which can reduce air flow and lead to anaerobic conditions.
- Turning also potentially assists the release of odorous gases that may have accumulated within the windrow voids and which would have otherwise oxidised as they moved through windrow. Research has shown that increased turning may increase the loss of ammonia gas in particular, which is odorous and its loss also reduces the nutrient value of the compost product.
- Specialised turners are more effective at turning and mechanical agitation and generally more efficient in terms of labour and time, compared to generic plant such as front-end loaders or excavators. However, over-use of windrow turners may have an adverse effect and the more gentle action of a front-end loader may be beneficial for some feedstock mixes.

Industry is increasingly considering a shift towards enclosed and/or forced aeration composting systems and some operators are already progressing towards this. This report notes that:

- Enclosed and forced aeration composting systems come in many forms but offer the potential of: more precise control over composting conditions; ensured continuous aerobic conditions; rapid pasteurisation and decomposition; and improved odour containment and control.
- Aerated static piles (ASPs) are the simplest form of forced aeration system and can be a cost-effective alternative to turned windrow systems. While there will be a moderate additional capital investment in the aeration floor / pipework and fan systems, there is usually reduced need for turning equipment and less land required for a given throughput as the process is more intense.
- Aeration rates need to be carefully controlled and balanced. Too much air will drive out heat and undermine pasteurisation, while it is also generally considered that increased rates of aeration result in a decrease in concentration of odorous compounds emitted, but an increase in total mass emissions. Operators need to determine the optimal aeration strategy for their particular compost mix through site trials and sampling in the commissioning phase.

Operations and Process Control

The following general findings were noted in terms of optimising site operations to minimise odour emissions:

- Highly putrescible feedstocks, which can be characterised by a high proportion of biodegradable volatile solids, often arrive at a composting facility in an anaerobic condition due to the time and way they have been stored by the waste generator. They also decompose rapidly in a composting environment and can quickly consume available oxygen. The solution to this issue is to blend and dilute highly putrescible or potentially odorous feedstocks with slowly degradable materials and bulking agents such as green waste in appropriate ratios to control the decomposition rate. Potentially odorous material must be combined in a mix as quickly as possible upon arrival at a composting facility.
- Preparing the right mix of feedstocks for composting is critical, with particular attention to C:N ratio, moisture content and porosity. The ideal C:N ratio for composting is in the range 25 to 40 and operators should understand and monitor the C and N content of their feedstocks, including lab analysis of samples as appropriate.
- Compost mixes outside the ideal range may still heat up and appear to be composting well. However, high C:N ratio mixes (low on nitrogen) will take longer to mature and increase the risk of odour formation in the curing piles. Low C:N ratio mixes (excessive nitrogen) can lead to loss of nitrogen as odorous ammonia gas.
- The optimum moisture content for composting is considered to be around 50% but some forced aeration systems perform better at slightly higher moisture contents of 55%. Above 60%, the pore spaces in the compost are filled with water, impeding air flow and leading to anaerobic conditions.
- It is generally better to focus on achieving an optimal C:N ratio whilst erring on the side of a drier mix. It is easy to add water to a mix, but difficult to remove moisture.
- The porosity of the mix (the proportion of free air space in the voids) should be above 40% and ideally in the range 55-65%. Bulk density is often used as a surrogate for porosity (there is a linear relationship) and is easy to measure on site. Bulk density of the mix should be below 650 kg/m3.
- The optimum pH level for most composting organisms is considered to be pH 5.5 to pH 8.0. Acidic conditions (low pH) are common in the initial phase of composting due to formation of organic acids but prolonged low pH conditions can lead to increased release of VOCs. High pH conditions can facilitate release of ammonia gas. The solution to managing pH levels is adjusting the C:N ratio of the initial mix, rather than direct adjustments, e.g. by adding lime.
- Temperature is an important (and relatively easy) parameter to monitor during the composting phase. The ideal range for thermophilic decomposition is around 45°C to 60°C, while 55°C is considered the minimum to achieve pasteurisation. Higher temperatures can increase the volatility of odorous compounds and there is a direct relationship between temperature and odour emissions up to around 65°C.
- Oxygen levels of 5% within the windrow voids is generally considered to be the minimum threshold for ‘aerobic’ composting, though above 10% is preferable.

The curing phase of composting, which follows the main active composting phase, can be a surprisingly significant source of odours, particularly when material is moved to this phase too soon:

- The thermophilic phase of composting in a well-managed system is not completed until temperatures start to consistently decline below 45°C, at which point, the curing or maturation phase can begin.

- The curing phase is important and can take anywhere from 1 to 6 months. The smell of mature compost should not be unpleasant, while immature compost may have an unpleasant odour and become anaerobic when stockpiled.
- Compost should not be screened until the latter stages of curing, to maintain the compost porosity. Stockpiling of screened compost that is not fully cured can contribute to odour issues.
- There are a number of ways to test the maturity of compost including the Solvita™ test which can be performed on site and is considered an acceptable method in the Australian Standard AS4454 and several European guidelines.

Composting Regulation

Upon reviewing the Environmental Authorities of Queensland composting facilities and regulatory approaches in other jurisdictions, it was noted that:

- Waste acceptance conditions in existing EAs vary widely with some licences having no or very few specific waste acceptance conditions stated. Similarly, there is inconsistency in the conditions that are intended to control odour impacts. Inconsistency in regulation between otherwise similar sites creates an un-level playing field commercially (real or perceived) which may be a barrier to investment in upgrades and improvements.
- Most EAs require an outcome of no odour nuisance at any sensitive place. Such outcome-based conditions place the onus on the operator to determine the best way to achieve that outcome. The challenge with this approach is that the outcome can be difficult to measure and if there are multiple potential sources of odour around a 'sensitive place', it can be difficult to link a nuisance issue to a specific activity or operator and enforce these types of conditions.
- Most other jurisdictions provide clear guidance in varying forms about acceptable locations for new composting facilities and particularly, separation distances to minimise amenity impacts on residents and sensitive receptors. Such guidance is helpful to operators and developers of new projects but is not a substitute for site specific assessment of the risks, through an odour impact assessment. The separation distance needs to factor in the local topography and climate, types of materials being processed, the technology and other engineering and operational controls in place.

Composting Feedstocks

This study has identified a long and varied list of over 100 different feedstock materials that are thought to be, or are permitted to be, used as composting feedstocks in Queensland. The feedstocks have been assessed at a high level for their odour contribution potential in a composting context, which is difficult to do quantitatively with the limited feedstock data available. The assessment consider factors which indicate high potential for odour formation such as putrescible content / biodegradability, likely state upon arrival at site (e.g. anaerobic), likely concentrations of nitrogen and sulfur compounds, and content of proteins, fats and oils.

The assessment identifies those feedstocks which pose a higher risk of causing or contributing to odour issues in a composting process, which will allow appropriate mitigation strategies to be targeted. A number of feedstocks have been identified as having a high or very high potential odour contribution in a composting process and should potentially be considered for increased operational and/or regulatory control as composting feedstocks.

It is noted that Phase 2 of this project will add to this assessment, by assessing the risk of contamination posed by composting feedstocks.

Understanding and Quantifying Odour

This report contains extensive information to assist readers to understand how odours from composting can be described and measured. It is noted that:

- Odour concentration is the most commonly used odour dimension to characterise an odour for regulatory purposes and is measurable by well-established olfactometry methods in a lab setting. However, other dimensions such as intensity, character, offensiveness and persistency are also important in assessing or describing a nuisance odour (together the CICOP dimensions of odour).
- The assessment of odour impact is complex. The FIDOL factors describe the key factors that influence the extent to which odours adversely affect communities – they include frequency, intensity, duration, offensiveness and location. There is some overlap with the CICOP dimensions which describe a particular odour, but the FIDOL factors are more specific to a site and community and can be used to assess odour impact of an operation.
- Composting facilities are typically characterised by multiple point and fugitive sources of odour (receival areas, open windrows, turning activities, maturation pads, leachate dams, biofilters), and are often sited in areas of relatively complex terrain. Odour dispersion modelling can be an effective tool to assess odour impact on receptors, taking into account these complex factors, provided the right type of model is used. Models can also help operators and regulators to understand the effects of different variables such as weather conditions.
- Odour emissions measurements taken on site are a critical part of odour dispersion modelling and impact assessment to maximise their accuracy
- Field odour surveys can be a useful tool to quantify and delineate an odour plume but they require careful planning and analysis of the data to provide a comprehensive assessment of nuisance potential and extent.
- Composting releases a complex mix of many different odorous compounds at different stages of the process and depending on the composition of the feedstock and process conditions. The compounds all behave and change differently as they travel through the atmosphere. Therefore, there is often little benefit in trying to trace odours by measuring specific isolated compounds in air.
- Most composting odours are associated with a range of different volatile organic compounds that are released and it is noted that:
  - Feedstocks which are high in nitrogen are prone to producing ammonia gas during composting which has a recognisable pungent odour. Although ammonia has been noted to have a high odour threshold (i.e. it takes relatively high concentrations to be detected) and to dissipate rapidly.
  - Sulfur containing materials such as food, paper, gypsum, manure and biosolids can lead to release of mercaptans and other volatile organic sulfur compounds, while anaerobic conditions in a compost pile can lead to release of hydrogen sulfide gas with its characteristic rotten egg smell which is offensive even at low concentrations.
  - Feedstocks high in proteins such as food waste, manures and animal processing wastes are particularly vulnerable to production of odorous compounds as they can release both volatile nitrogen and sulfur based compounds.
  - Anaerobic conditions within a composting pile lead to formation and accumulation of particularly odorous compounds.
- Odour balance studies of composting facilities overseas, which measure the odour emission factors from different parts of the process have found that for high odour potential, rapidly biodegradable feedstocks (such as MSW organics) the main composting phase accounts for most of the odour emissions. For slower degrading

materials such as green waste, the odour emissions are more evenly spread across the entire process from receival to final product storage. In both cases, the curing phase was also a significant odour source and this is consistent with other studies which have shown curing can be responsible for more odour release than the main composting stage.

- Weather has an impact on odour emissions and in Queensland's warm climate the tipping or receival area can be a major source of odours due to waste significantly decomposing in the heat before it arrives on site, which is less of an issue in colder climates.
- Typically, poor dispersion of odour emissions from composting facilities occurs during light stable wind conditions, particularly during the evening and early morning when odour emissions can become entrained within slowly flowing air flows, travelling with little dilution along the path from source to receptor.
- On the other hand, moderate wind speeds may strip or draw out odorous compounds from a windrow resulting in a significant, well-defined and concentrated odour plume, which may be transported considerable distances downwind.
- Meteorological data collected onsite at a composting facility can be extremely useful when responding to complaints, planning site operations to minimise odour impact or for use within an atmospheric dispersion model. Meteorological observations can be carefully analysed to help an operator understand the dispersion mechanisms governing their odour plume, which can provide useful odour mitigation insights. Weather stations have to be carefully sited, typically 10 metres above the ground, following the appropriate Australian Standard.

Odour Treatment

In composting operations, it is far more effective to avoid or minimise the formation of odours at source, than to try to capture and treat them. That said there are treatment options and it is noted that:

- It is difficult to apply odour treatment techniques to open windrow composting but one option which has been found to be effective is to apply a 'cap' of matured compost (up to 150-200mm thick if unscreened) on top of a newly formed windrow. The layer acts as a biofilter and can be very effective at reducing VOC emissions. After the first turning, the mature compost gets mixed into the compost where it acts as an inoculum and continues to have a beneficial impact.
- Where process emissions can be captured, such as in an enclosed or covered system or an aerated static pile operating in suction mode, the odours can be effectively treated through an engineered biofilter. Biofilters provide a high rate of odour removal efficiency for a moderate capital cost and low operating costs.
- Wet scrubbing systems can be used to treat particularly strong odorous air streams, often as a pre-treatment to a biofilter.
- Other physical and chemical treatments are available but have experienced limited application or success on composting facilities.
- Chemical masking agents, often applied as a fog or mist over a site, have been used at composting facilities but their efficacy is debatable and they can actually contribute to the odour nuisance.

Recommendations

A number of preliminary recommendations are proposed in this report, which will be further developed and added to in Phase 2 of the project.

Operational and Process Controls

The following recommendations are made to assist in improving odour management at composting facilities, based on knowledge of current processes and discussion of best practice methods in this report.

1. Turned windrow management – there is no best practice standard for the frequency and method of turning. Turning methods and schedules need to be optimised for the feedstock mix and site requirements. This requires a balancing of several factors and the optimal turning strategy should be determined by an experienced operator through site trials and measurements.
2. That said, there are some common considerations in optimising turning the strategy:
    - Focus on adequate porosity - mix odorous materials with a generous and appropriate ratio of bulking material (e.g. shredded green waste) with particles that are not too small.
    - Minimise turning events for windrows containing odorous feedstocks, especially during the first 7-10 days of composting, with only the minimum turning required to support pasteurisation and moisture redistribution. This enables the odorous by-products generated during this initial phase to be oxidised to less odorous compounds before they are released to the atmosphere. The compounds will continue to decompose as they move through the windrow mass.
    - When turning with a front end loader, ensure that the operators do not drive up on the compost when windrows are being formed, which can cause compaction and reduce airflow.
3. Composters processing odorous materials in open windrows should be encouraged to experiment with caps of mature compost as a measure to reduce odour emissions during the initial stage of composting.
4. Composting operations that process highly odorous materials and/or are located close to sensitive receptors should consider and assess the implementation of some form of forced aeration and/or enclosed composting process, for at least the initial phase of composting.
5. Forced aeration if used, needs to be optimised for a particular compost mix, so as not to have an adverse impact on odour emissions.
6. Engineered biofilters are a very efficient and cost effective method of treating odours if they can be captured from an enclosed or forced aeration composting system. They could similarly be applied to treat air from an enclosed feedstock receival and mixing building.
7. For best practice feedstock receival, operators should:
    - Keep an ample stockpile of bulking agent or high carbon material at the receiving area to immediately mix with all deliveries of odorous materials
    - Immediately mix potentially odorous materials upon receipt and ensure that materials are mixed uniformly throughout
    - Consider enclosing the receival facilities for highly odorous materials and the initial mixing operation, with appropriate ventilation and biofilter systems
    - Consider blanketing odorous solid materials with a thick layer of bulking agent
    - Work with generators and collectors to increase collection frequency
    - Have a system in place to assess and reject unacceptably odorous materials and eliminate troublesome feedstock sources

- Undertake small scale trials of new feedstocks prior to accepting regular full loads, to assess the practical aspects of handling the new material and to monitor its performance in a composting pile.

8. Operators should have a clear procedure in place to ensure the initial compost mix is optimal in terms of C:N ratio, moisture and porosity and to understand the odour potential of each feedstock (e.g. including nitrogen and sulfur content). This should include testing and analysis of feedstocks to understand their physicochemical characteristics. Such testing need not be of every load for consistent feedstocks, but sufficient to understand the key parameters and variability.
9. Parameters such as temperature and pH should be regularly monitored throughout the composting process. Other parameters such as moisture content and oxygen levels may also be useful, particularly when processing wet or odorous feedstocks or optimising the process.
10. Compost piles should not be moved to the maturation or curing stage until the thermophilic stage of composting has been completed, indicated by consistent temperatures below 45°C (assuming all other aspects managed correctly).
11. Maturity tests such as Solvita™ are widely accepted and can be done on site, to ensure compost is mature enough to be safely stored.

Regulation

12. DES should investigate options to harmonise and reduce the inconsistency in EA conditions for composting operations with a similar risk profile and implement consistent minimum standards on key aspects such as waste acceptance (including testing requirements), product quality and odour control. There are good examples of effective conditions amongst some of the more recent existing EAs which may serve as a template, but the main focus should be on achieving consistency. The initial (and so far, limited) feedback from industry suggests they are open to changes provided it applies consistently to all and 'levels the playing field'.
13. DES should consider whether there is a need for more stringent regulation or conditioning on sites that receive feedstocks considered to have a high or very high contribution to odour risk (as assessed in this report). This is not to suggest that these feedstocks are not suitable for composting, but that additional control measures may be warranted such as maximum blending ratios in green waste, additional requirements for their storage and mixing, more sophisticated processing, or additional analysis and documentation requirements.
14. With respect to odour, DES should consider whether the current outcomes-based approach is appropriate for regulating odours from composting facilities. Outcome based conditions are challenging to enforce when the outcome is difficult to measure and quantify or to trace back to a specific activity. Even more so when there are multiple operators potentially having a similar impact in one area, as is the case at Swanbank and elsewhere. Those existing conditions could be supplemented with additional conditions which address the root causes of odour as discussed in this report (e.g. feedstock storage and blending; windrow mixing and turning; maintaining aerobic conditions; and monitoring of key process parameters). There is a fine balance to be struck between being overly-prescriptive and maintaining flexibility for lower risk applications, which other states have not necessarily achieved. Therefore a Queensland specific approach is recommended, considering some of the operational methods noted in this report.
15. It is apparent that waste collectors and transporters exert a high degree of power within the organic waste management supply chain, yet it is the composters at the end of that chain that feel they bear the brunt of regulation. In considering how to better regulate the composting industry, DES should be cognisant of this and consider options to better regulate the whole supply chain, making sure that waste

generators and transporters are taking responsibility for providing adequate and accurate information about their waste streams, and ensuring they are managed appropriately. The new amendments under the Regulated Waste Framework will go some way to addressing this, provided they are properly applied by all parties in the supply chain and enforced by DES.

16. It is also apparent that the current waste tracking system is ineffective at tracking and flagging anomalous waste movements which may indicate waste has been taken to an inappropriate facility. DES should consider options to upgrade or overhaul the Waste Tracking System to an electronic platform that ensures that critical information is accessible to transporters, operators and the regulator in real time. This could potentially stop, for example, transporters 'shopping around' for a disposal option after being rejected from one facility.

17. For new facilities, industry could benefit from clear guidance produced by DES on the regulation of composting facilities including aspects such as locating composting facilities, separation distances, process and operational controls to minimise odour issues. Guidance documents from other states provide examples which may be considered, but the guidance should be tailored to Queensland context, be risk-based and allow a degree of flexibility for low risk applications.

18. To improve standards at existing facilities, industry seems open to development of minimum standards or a code of practice and generally lifting operational standards and knowledge levels. However, commercial competition means that such measures are unlikely to be developed by industry in isolation. Government may have a role to play in leading and facilitating the collaborative development of minimum standards and training requirements. Consideration would need to be given as to how to incentivise existing operators to comply with the standards.

Assessing odour from composting facilities

This report contains extensive information about different odour assessment and measurement techniques. It is apparent that some major composters in Queensland have rather limited technical understanding of how odours are caused and dispersed in the atmosphere, and it seems that the use of odour measurement and modelling as tools to inform that understanding for their specific site is limited. As such, the project team recommends more robust assessment and analysis of odour sources and dispersion through modelling and sampling as follows.

19. For any new proposed composting facilities, an odour impact assessment should be undertaken as part of the site's environmental and development approval processes. The assessment may vary depending on the risk posed by the scale, feedstocks and location of the facility.

20. For higher risk facilities, once it is approved and commences operation, an odour emissions audit should be conducted to develop a representative odour emissions inventory of the site's operations. Once operational data is collected, it can be fed back into the site odour dispersion model (developed for the facility's environmental approvals) to calibrate and refine the model.

    The odour impact assessment can then be reviewed to evaluate whether the facility is likely to comply with the conditions under which it was approved, or whether further control measures may be warranted to ensure ongoing compliance. The calibrated dispersion model will then be a valuable tool for the operator to understand how their operation can impact on sensitive receptors under different conditions.

    The performance of the odour dispersion model generated for the actual operating conditions could be evaluated and verified through a series of field ambient odour assessments.

21. For an existing composting facility that has been the subject of a certain number of complaints (to be determined by the regulator) from the community related to offensive odours that may cause nuisance, the proponent of the facility should be required to conduct an odour impact assessment of its operations.

22. For all facilities, operators should undertake an odour audit or odour balance study which can be a useful exercise to identify and quantify odour emissions from each stage of the process, resulting in an odour emissions inventory for the site. This will vary for each site but it is worth noting the receival area and curing piles can be major odour sources, in addition to the mixing and composting stages.

23. Ongoing environmental management of existing and future composting facilities should include, but not be limited to:
    - A site-specific odour management plan, the purpose of which is to identify odour sources and proactively reduce the potential for odour generation as well as to have a reactive plan for managing odour during upset conditions.
    - Site-specific meteorological data should be collected and recorded on site in accordance with appropriate standards.
    - All complaints reported to the occupier regarding odour must be considered in the light of meteorological data and/or site activities such as delivery of unusual organics to identify any correlations.

Swanbank Composting Improvements

As part of the Phase 1 investigations for this study, the project team reviewed two major composting facilities currently operating in South East Queensland and developed detailed case studies of their operations. Detailed findings are contained in a separate commercial-in-confidence report appended to this report. Based on the review of the two Swanbank composting facilities, a number of common actions or areas for improvement were identified which are in line with industry best practice and could potentially be applied more broadly:

24. Operators receiving odorous liquid and other materials in sensitive areas should consider enclosing the reception and storage facilities for those feedstocks as well as the feedstock mixing areas, within an airtight structure along with air extraction to a biofilter.

25. Operators should implement operational procedures to avoid or minimise the formation of leachate through appropriate solid and liquid blending ratios and efficient methods of mixing the materials.

26. Where leachate is generated and storage is unavoidable, it should be able to drain freely from all operational areas and stored in an aerated pond to maintain aerobic conditions, or in enclosed tanks with adequate ventilation systems. Leachate storages should have adequate capacity to avoid uncontrolled overflows in heavy rainfall and be regularly desilted to prevent excessive accumulation of organic solids, which leads to anaerobic and odorous conditions.

27. Operators using open windrows should consider simple methods of mitigating odour from windrows in the early stages of composting, such as application of a thick layer or blanket of mature compost (unscreened or oversize fraction) and/or pure green waste mulch over the windrows once they are initially formed.

28. Large scale and higher risk composting facilities should be encouraged to develop an odour dispersion model, together with on-ground sampling to calibrate the modelling, to better understand the impact of different point and fugitive odour sources and activities, and the effects of different weather conditions.

29. Operators should provide training of staff to understand odour causes, dispersion and best practice control methods. DES can potentially support by developing technical guidance materials and manuals.

1 INTRODUCTION

Arcadis has been engaged by the Department of Environment and Science (DES) to undertake a critical assessment, review and evaluation of composting operations in Queensland with a focus on odour management, feedstock suitability, contamination risks and the regulation of these aspects by DES.

Composting in Queensland is a significant industry which in 2017-18 converted 1.4 million tonnes of organic residues and waste into beneficial products which generally improve soil health and quality. There are around 25 companies of varying scales whose primary business is composting plus a number of other companies and councils that engage in organics processing in various forms.

Without a successful composting industry, significantly more organic waste would be landfilled or otherwise disposed to land without processing, resulting in a range of environmental and social impacts including significant greenhouse gas emissions.

The role of composting in the broader waste management system is set to grow over the coming years as councils and businesses look for ways to divert more organic waste from landfill, particularly food waste. The draft Queensland Waste Strategy sets ambitious targets for recycling waste and reducing landfill which will only be achieved if more organics are recovered and directed to beneficial uses. The Waste Strategy focuses on building a circular economy in Queensland and the recovery of organic waste is already a major contributor to that.

However, composting also has a high potential to impact on local communities and the environment. The Queensland Government has committed to reducing those impacts with a particular focus on addressing odour management issues and contamination of compost products, arising from the use of inappropriate feedstocks.

As such, the Department has commissioned the current study to:

- Ensure that waste acceptance criteria imposed in Environmental Authorities is adequate to protect surrounding communities from nuisance odours.
- Look at the materials the Swanbank industries currently accept for composting and determine whether any changes are required.
- Scientifically review the Environmental Authority waste acceptance criteria for composting operations.

DES has noted that in the past, composting operators have traditionally used organic waste streams such as green waste and some clean inorganic waste streams in the manufacturing of compost and soil products. However, in recent years, the activities of the industry have shifted to see a proliferation in the types and nature of organic and inorganic waste streams incorporated into compost. Concerns have been raised about the suitability of some of these materials in compost.

At the same time, DES has received a considerable number of complaints about odour nuisance from composting operations, particularly in the Swanbank area near Ipswich, but also near other composting operations. DES has established the Swanbank Odour Abatement Taskforce which has, and continues to, conduct extensive odour investigations in that particular area. DES considers there are opportunities to improve the regulation of nuisance odour from composting operations in Swanbank and more broadly across Queensland.

This study aims to improve the Department's understanding of composting processes and odour emissions from composting; best practice management of composting; the suitability of different materials as feedstocks in composting and requirements for improving regulation of the industry.

1.1 Scope and purpose

This project is taking a holistic view of the composting industry in Queensland and compiling expert advice on best practice environmental management for composting operations and the suitability of different waste streams in the manufacture of compost and soil conditioners. It will also provide advice in relation to potential adverse consequences from wastes used in composting and any regulatory changes to address these.

The study will aim to improve the Department's understanding of:

- odorous air emission sources arising from composting operations;
- best practice management of composting facilities;
- the suitability of various waste streams (feedstocks) in the manufacture of compost and soil conditioner products and how these feedstocks should be managed;
- requirements for improved regulation.

The study is being undertaken in two key phases.

Phase 1, the findings of which are presented in this report, is a review of composting operations with a focus on odour sources, management practices and regulation, using facilities in the Swanbank Industrial Area as a case study. It includes:

- An extensive review of the source of odorous air emissions arising from composting activities generally, including sources of odour, odour management practices, effect of climatic conditions, effectiveness of odour management controls and/or practices and any environmental authority conditions (or lack thereof) that may result in the release of offensive odorous air emissions affecting surrounding sensitive receptors. This includes a review or relevant literature.
- Identification of odorous feedstocks in compost and soil conditioners and management practices that may result in odour impact on sensitive receptors, in the absence of appropriate management practices. Report on national and international best practice management, standards and methodologies at composting facilities to manage odour risk and odorous feedstock.
- To inform the above, an investigation of composting operations within the Swanbank Industrial Area has been undertaken. Two case studies of major composting facilities have been developed with consideration of potential odour sources and any management practices that may give rise to offensive odorous air emissions, resulting in impacts to surrounding residents and other sensitive receptors.

Phase 2 focuses on managing contaminants in compost products, involving a critical review of the suitability of compost feedstocks and identifying the risks to the environment with regard to the unrestricted distribution of the manufactured products.

The results of the Phase 2 investigations will be reported separately in a subsequent report.

1.2 Report structure

This report presents the findings of the Phase 1 investigation into composting operations and the management of odour issues in composting. The report is structured as follows:

- Chapter 2 provides an overview of the composting process and different techniques and technologies, as well as key process control aspects and their impact on odour emissions.

- Chapter 3 provides an overview of composting regulation in Queensland with a particular focus on Environmental Authorities issued to existing composting facilities and conditions imposed to manage odour and around waste acceptance.
- Chapter 4 identifies the wide range of feedstocks used in Queensland composting facilities and a high level assessment of their likely contribution to odour issues.
- Chapter 5 provides an overview of odour and its measurement and assessment, including methods to quantify and describe the different elements of odour.
- Chapter 6 describes approaches to assessing odour impact, including the key aspects that determine the impact of odours on the community.
- Chapter 7 focuses on identifying and quantifying the specific chemical compounds that are responsible for odours from composting.
- Chapter 8 reviews a range of potential techniques to treat and reduce odours from composting.
- Chapter 9 reviews different approaches to compost regulation in Queensland compared to other jurisdictions in Australia and internationally.
- Chapter 10 provides an overview of the findings of the Swanbank composting case studies, which are detailed in a separate commercial-in-confidence report, attached as Appendix B.
- Chapter 11 provides preliminary recommendations arising from the Phase 1 review, noting that further recommendations will be developed in Phase 2, which also includes further industry consultation to co-design regulatory responses.

At the end of each chapter is a summary of key findings from that chapter and recommendations arising.

1.3 Project team

Arcadis is a global engineering and environmental consultancy which in Australia, is a leading provider of strategic and technical advice on waste management to local and state governments and private industry. In undertaking the study, Arcadis has partnered with a team of specialists including:

- Air Environment is one of Australia's leading air quality and odour assessment and management consultancies. Air Environment is led by Andrew Balch and Brisbane based, bringing extensive experience in assessing odour issues in relation to composting and waste management facilities. AE's role on the project is to advise on odour management, measurement and assessment aspects.
- Frontier Ag and Environment, led by Kevin Wilkinson, is a specialist consultancy providing advice on organics processing and the use of organic soil amendments for soil and crop health. Frontier Ag and Environment is providing specialist input on composting knowledge and science and best practice management.
- The Centre for Recycling of Organic Waste and Nutrients (CROWN) at the University of Queensland, led by Johannes Biala. CROWN is an independent research, training and advisory organisation that covers all aspects of organics recycling and resource recovery supply chains. It is part-funded by the Department of Environment and Science. CROWN's role on the project is to contribute research and technical advice on best practice composting methods and contaminant assessment / management.

Arcadis acknowledges and thanks the project partners for their valuable contributions.

As part of the study, the project team consulted extensively with two composting operators to develop detailed case studies of their facilities, as discussed in Chapter 10. The project team extends our thanks to those operators for their openness and willingness to support the study, and their valuable insights and information.

2 COMPOSTING BACKGROUND AND BEST PRACTICE

This chapter provides an overview of composting processes, technologies and process control parameters with a particular focus on their impact on odour generation and release.

2.1 The Composting Process

Composting is the controlled biological decomposition of organic materials under aerobic and thermophilic or naturally self-heating conditions (Wilkinson *et al.* 1998). Industrial scale composting is a controlled process, like any other manufacturing process. Failure to adequately control composting process parameters can rapidly lead to adverse environmental and public health impacts and poor product quality. This is particularly true in that composting is a biological process and the organisms involved need the right environmental conditions to thrive.

Composting is an aerobic process in that the decomposition of organic materials takes place in the presence of air and the orgsanisms need oxygen to biodegrade materials. Failure to ensure adequate air flow and maintain composting conditions in an aerobic state, slows the composting process and results in anaerobic conditions that lead to nuisance odours.

Composting is also a thermophilic process, meaning that heat is produced naturally by the process and it takes place at temperatures above 45°C for extended periods during processing. Thermophilic composting is desirable for a number of reasons – it results in faster rates of decomposition, speeding up the composting process, and it has a pasteurisation effect - assisting in the elimination of pathogens and weed seeds that might be present in the feedstock material. Managing oxygenation and temperature in a compost pile are key process control variables in composting, and commercial composters must understand what role they play in the generation and management of odours during composting.

Whilst composting is principally a biologically mediated process, decomposition itself can be described as a series of chemical reactions in which complex biochemical compounds are broken down into their constituent parts. The main components of most organic materials are proteins, carbohydrates and fats,; containing various combinations of carbon, hydrogen, oxygen, nitrogen and sulfur. These materials decompose following a sequence of steps, as shown for a simple hydrocarbon in the example below (Coker 2012):

Hydrocarbon > alcohol > aldehyde > acid > water and carbon dioxide

Similarly, proteins will decompose into their constituent polypeptides, which in turn, break down into amino acids. Each category of decomposition has several subcategories, many of which are intermediate byproducts of the decomposition process.

During the thermophilic stage of composting, a vast number of reactions take place simultaneously. The dynamic character of decomposition during composting is typically described in general terms due to its complexity. This dynamism is associated with the complex inter-relationship that exists between food source (feedstock), environmental conditions (e.g. temperature, air and water) and metabolic activity (microbial species, diversity and activity) as depicted in Figure 1.

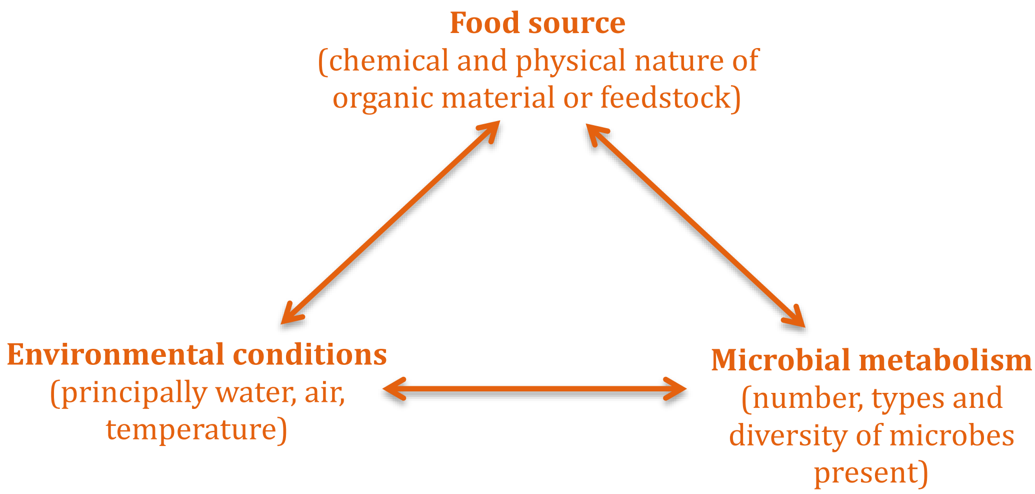

Figure 1: Overview of complex inter-relationships in composting reactions

Understanding these relationships in general terms is critical to successful composting including how odours are generated and managed. As the composting process advances for each batch, different decomposition products are produced, resulting in changes to the character of odour generated over time (Coker 2012). Odorous compounds are interactive or synergistic, not additive, in their effect. In other words, a combination of odorous compounds is often perceived by the senses as one unique odour, rather than several odours acting independently.

This makes it difficult to identify reliable chemical indicators for odours caused by complex biological materials (Zhang *et al.* 2009). While it is possible to measure the concentration of individual chemicals in odour emissions, this knowledge is of limited real-world value in assessing odour problems. Olfactometry, or using the human sense of smell, therefore, remains as the industry and regulatory standard, and provides the best possible method currently available for odour evaluation (Zhang *et al.* 2009).

2.2 Composting systems

Potential odour problems from a composting facility should be anticipated and addressed at the design and planning stage of a new facility, since it is much more difficult to deal with nuisance odours retrospectively (DEFRA 2009[1]). The choice of composting technology is one of many aspects that will affect the odour potential of a process. Other key factors include the site location (see Chapter 0) and proximity to sensitive receptors (e.g. residences, education and medical facilities, public areas, workplaces), local climate and prevailing weather conditions and local terrain.

This section discusses the characteristics of the main categories of composting technologies with a particular emphasis on odour control. Within each major category, there are many different sub-types and variants of technologies, all with differing degrees of control measures to manage odours.

Once a facility is established and operational, the next lines of defense against any problems in composting in order of importance are as follows:

- Understanding the risks associated with any given feedstock;

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1 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/228738/7599.pdf

- Getting the physicochemical characteristics of the mix right;
- Careful process control and monitoring; and
- The implementation of prevention strategies to circumvent potential problems.

These issues are discussed in Chapter 2.3.

Even a well-located and designed composting facility with the most sophisticated enclosed technology can fail without due care being taken in the areas listed above. There are examples of fully enclosed composting facilities suffering from major odour issues including some of the alternate waste treatment (AWT) plants currently in operation around Australia which process organics extracted from mixed household waste. For example, the AWT plant operated by Southern Metropolitan Regional Council in Perth was the source of significant ongoing odour complaints over its first decade of operations, leading to further investment in odour treatment systems.

2.2.1 Turned windrows

The most common type of composting system in Queensland and Australia is the turned open windrow. Windrows can be turned either with a front-end loader, excavator or specialised windrow turning machines.

The size and shape of windrows depends on the materials being composted and the type of machinery used to turn the windrows (Wilkinson *et al.* 1998). Windrows established and turned by front-end loader are usually 2 to 3.5 m high and 3 to 6 m at the base. Windrows turned by self-propelled windrow turners are usually lower in height (1.2 to 2.8 m), depending on the passage height of the turner used. Windrows can be as long as convenient but are usually between 20 and 50 m long. Windrows that are too large (e.g. height >3.5 m) can overheat easily and develop anaerobic conditions, whilst windrows that are too small (height 1 m or less) may fail to heat up at all due to heat loss from the windrow surface.

In general, specialised turners are more effective at turning and mechanical agitation than front-end loaders. They are certainly more effective at breaking up anaerobic clumps in feedstocks that tend to ball up. For example, the nature of some feedstocks, like fruit and vegetables, are such that they tend to roll off and accumulate at the base of piles when a front-end loader is used for turning (Coker 2012). These situations can be the source of odorous emissions. In these cases, the more aggressive action of a specialised windrow turner may be more suitable to break up and distribute such feedstock throughout a compost pile. Still, care must be taken not to overwork a windrow, especially where windrow turners are concerned. An aggressive turning schedule can reduce the porosity of a windrow by reducing the size of compost particles and therefore free air space (Buckner 2002).

Although windrow turning frequency has much less of an impact on composting than other process variables such as feedstock composition, moisture content and windrow size (Michel *et al.* 1996), it has been reported to influence such things as the rate of decomposition (Buckner 2002; Parkinson *et al.* 2004), compost bulk density (Tirado and Michel 2010), and the time required to reach maturation (Chikae *et al.* 2006). Yet, increased turning frequency does not necessarily correlate well with compost quality. For example, Tirado and Michel (2010) found that dairy manure composted in larger windrows turned three times per month resulted in composts not significantly different than those made in smaller windrows turned 10 times per month.

It is commonly considered that turning is critical to maintaining aerobic conditions within a windrow. In fact, research suggests that turning may actually have little impact on oxygen levels in a pile since the oxygen that is re-introduced is quickly consumed within a few hours of turning (Michel *et al.* 1996; Tirado and Michel 2010). This problem again highlights the importance of achieving the correct porosity of a compost mix, which has a far greater bearing on oxygen levels.

Aerobic conditions cannot be maintained in a compost mix of low porosity simply by increasing the rate of turning for it is not desirable or economically feasible to turn a compost pile every few hours. This was effectively demonstrated by Buckner (2002) who studied the effect of turning frequency on odour concentrations in windrows comprising of different types of green waste mixes (grass clippings, leaves and wood chips). Changes in odour concentration in leaf/grass windrows fluctuated erratically regardless of turning frequency, whereas grass/wood chip mixtures benefited from additional turning. Low odour concentrations were generally only achieved in windrows with mean oxygen concentrations of 10% or more. A bulking agent like wood chips or woody green waste provides the structural component required for supporting high interspatial oxygen concentrations and natural air flow, but there are significant trade-offs. They add little value to the finished compost and increase the volume of materials on site. Furthermore, they may require additional handling by way of grinding, mixing and screening (Buckner 2002).

On the other hand, turning also potentially assists the release of odorous gases from within the windrow voids. Other research has shown that increased turning may have negative impacts from loss of NH_3 (ammonia, an odorous gas) (Tirado and Michel 2010). Ammonia is a pungent odorous gas but the loss of ammonia from compost also represents a loss of nitrogen from the finished product, reducing it nutrient content. The effect of turning on losses of greenhouse gasses (such as CH_4 and N_2O) is less clear because different researchers have shown both decreases and increases in emissions as a result of turning (Ahn *et al.* 2011; Chen *et al.* 2015).

Because turning introduces air, improves the distribution of water and nutrients and may improve porosity, it advances the composting process and improves odour control in the long run (CIWMB 2007). However, the same authors state that:

> *'there is some debate about whether the frequent release of moderate odours from frequent turning is more damaging than the infrequent release of strong odours from infrequent turning. Composting operators have expressed contrasting opinions. Research provides little guidance on this point'.*

In summing up, the physicochemical composition of the feedstock is the key to establishing and maintaining the consistent aerobic conditions necessary for low odour emissions, regardless of composting system. Turning has limited direct impact on maintaining aerobic conditions but can be important for maintaining porosity and voids within the windrow structure and redistributing moisture which may otherwise lead to anaerobic pockets. Therefore, there is no standard for optimised turning - turning methods and schedules need to be developed to match feedstock and site requirements and balance the various parameters noted above.

For some sites, a custom-designed windrow turner will deliver optimal results, while for other processes and feedstock mixes, the more gentle turning action of a front-end loader may be beneficial. Determining the optimal approach requires consideration of the feedstock types and characteristics. For example, if green waste is being used as a bulking agent to provide the necessary porosity and air flow through the windrow, is the particle size large enough to facilitate this. If liquids are being mixed with green waste, how many turning events are required to ensure even distribution and absorption of those liquids.

In most cases, these factors will be determined through experience and trial and error by operators. It should be incumbent on the operator to undertake such process optimisation trials to demonstrate that different turning methods have been assessed and that the chosen method is appropriate. This may be supported by site measurements to demonstrate that optimal conditions are being achieved (e.g. temperature profiles, moisture distribution, oxygen levels) as well as observations around particle size and porosity.

Particular attention should be given to the first few weeks of composting, when odour emissions are typically at their peak (Buckner 2002; Coker 2012). Some argue that turning frequency should be minimised in windrow systems taking into account the number of turns required to have minimal effects on the rate of compost production, and to ensure effective pasteurisation of the feedstock (Tirado and Michel 2010; Parkinson *et al.* 2004). The Australian Standard (AS4454) recommends a minimum of 3 turns for pasteurisation of green wastes, or 5 turns for higher risk materials over a minimum of 15 days. It should be noted that this recommendation is the minimum requirement to achieve pasteurisation and does not consider other operational parameters (e.g. temperature, moisture, oxygen levels) required to produce a fully mature compost product – i.e. maturation of compost takes far longer than 15 days and compost would typically need to be turned at regular intervals throughout the process.

Managing the moisture content of compost is another major process control variable for composting. As a general rule, replenishing water in windrows is best achieved just prior to, or during, turning events to ensure even distribution. Sprinklers, soaker hoses or fine-mist sprays can be effective means to do this, but it is difficult to get water to penetrate the full profile of a windrow without turning. Since many odorous gases are soluble in water, such an approach can also assist in knocking down odour emissions during turning.

Other approaches that can be used to minimise odour issues in turned windrow systems include (Coker 2012):

- Minimise turning events for windrows comprising odorous feedstocks, especially during the first 7-10 days of composting. This enables the odorous by-products produced during this initial phase to be oxidised to less odorous compounds before they are released to the atmosphere. The compounds will continue to decompose as they move through the windrow mass. This needs to be considered in the context of the feedstock mix though – high moisture content mixes will benefit from turning to redistribute the moisture.
- Ensuring that loader operators do not drive up on the compost when windrows are being formed (this can cause compaction and reduce airflow);
- Leaving enough room around windrows for equipment access for implementing odour-related best management practices (BMPs) as needed;
- Covering odorous windrows with a 75 to 100 mm layer of finished compost to act as a biofilter for emissions from the windrow surface (thicker for unscreened material which may be more effective). Further detail on biofilters is covered in Section 8.1;
- Through diligent housekeeping and site management.

Coker also suggests that covering windrows either under a roof or with textile covers (e.g. proprietary Fabcom® or Gore® Waste Covers) is effective at controlling odours from windrows. Covering of windrows prevents the generation of odorous leachate during heavy and/or prolonged rain. Textile covers, while being breathable, reduce evaporation and therefore reduce the need for additional watering during the composting process. Condensation under the covers of a windrow also helps to trap odorous compounds so that they can be oxidised in situ. However, covers are generally used together with forced aeration systems to maintain aerobic conditions; and these systems are discussed further in 2.2.2 below.

2.2.2 Forced aeration and enclosed systems

Forced aeration systems can take a number of different forms, from aerated static piles or windrows, bag systems, bunker systems, agitated bays and in-vessel systems such as tunnels. These systems are generally more capital intensive than windrow-composting facilities, though the potential range in cost is extremely wide, depending on the type of technology used and its scale.

These systems are typically favored by regulatory authorities for processing of odorous organics throughout the world due their perceived advantages. These are as follows:

- Precise process control of composting conditions (temperature, aeration and moisture addition);
- Rapid pasteurisation and rapid rates of decomposition due to more uniform distribution of high temperatures occurring throughout the compost matrix;
- They are often established under a roof, in a building or vessel, providing protection from the elements; and
- They typically are associated with improved systems for odour containment and control.

This report focuses on composting, but anaerobic digestion is also an alternative biological processing method for some organic wastes which is fully enclosed and offers many of the same advantages as enclosed composting.

Liquid and high moisture content wastes can be processed through wet AD systems, of which there are several reference examples in Queensland and Australia processing streams such as animal manures, sewage sludge / biosolids, food and food processing wastes. Dry AD systems are more suited to processing woody organics such as green waste and are gaining popularity in Europe and North America as an alternative to in-vessel composting. All AD facilities decompose organic waste under anaerobic conditions to produce methane rich biogas which can be used for energy purposes.

AD is not considered in detail in this report but is a potential alternative to composting for processing highly odorous waste streams. It has not generally been commercially viable other than in the discrete applications noted above, due to the prominence of low cost open windrow composting and/or relatively cheap landfill. The introduction of the landfill levy and associated funding programs may support the broader implementation of AD in Queensland and there are a number of proponents exploring this option.

The most efficient composting systems are arguably those that involve both forced aeration and mechanical agitation (the best of both worlds), but these are also the most expensive systems to implement.

A major advantage of forced aeration systems is the ability to control the rate of airflow through the compost matrix. Aeration rate is used as a primary operational tool for the maintenance of aerobic conditions and for temperature control in forced aeration systems. The rate of aeration needs to be carefully controlled and ideally respond to other parameters such as temperature – too much aeration will disperse the natural heat and preclude pasteurisation while drying out the material.

Other key advantages include:

- More rapid decomposition, which can shorten the total composting residence time and reduce the land footprint required, and
- Reduced need for turning

With respect to odour management, the following general principle typically applies:

- Increased rates of aeration result in a decrease in concentration of odorous compounds, but an increase in total mass emissions;
- Conversely, a decrease in aeration results in increased concentration but decreased total emissions (Walker 1993).

Ammonia and VOC emissions, two key odour chemical groups, can be differently affected by aeration rate. For example, in studies with pig manure, Elwell *et al.* (2001) showed that a 75% reduction in airflow resulted in a 50% reduction in ammonia emissions along with significant reductions (33-68%) in acetic, propionic, and butyric acid (VOCs) emissions. However, a similar airflow reduction resulted in an increase in emissions of other VOCs (isobutyric, isovaleric, and valeric acid) by up to 151%.

Zhang et al. (2009) found the optimal aeration strategy for odour control to be approximately 0.6 L/min.kg dry matter with intermittent aeration and a duty cycle of 33% for mixes comprised of poultry manure, sawdust and wood chips. However, the general conclusion is that the optimal aeration strategy needs to be determined for each specific feedstock mix, usually through site trials and sampling in the commissioning phase.

It is also generally held that higher temperatures lead to higher potential emissions of odorous compounds (Haug 1993). For example, Day *et al.* (1999) found that the concentrations of some odorous compounds such as pinene and ethyl butyrate could be 10-fold higher when composting pile temperature increased from 20 to 65°C. Zhang *et al.* (2009) found this principle held up to a set-point of about 60°C, beyond which the rate of odour emissions started to fall rapidly. In fact, increasing the temperature from 55 to 60°C doubled total odour emissions, whereas, an increase from 60 to 65°C reduced odour emission by 14%. At 70°C odour emissions were reduced by 46%. Furthermore, odour concentrations in that study were significant only in the first four days of composting and peaked on day 2 regardless of treatment.

Care must be taken in forced aeration systems to ensure that elevated aeration rates do not strip odorants out of a pile before they have had time to fully oxidise and decompose. This can be a problem if the fans strip odorants out of air-starved portions of the pile, putting pressure on the external odour control system (e.g., biofilter, if there is one) to handle the load (Coker 2012).

Aerated static piles (ASPs) can be a good option for processing large volumes of organic materials on a smaller footprint than turned windrow systems. ASPs can be as long as windrows, but many times wider since less room is required for access by turning equipment (an ASP is static during the active composting phase).

Aeration in ASPs is supplied through either holes in the concrete floor or via pipes laid on the ground below piles. Aeration can be supplied by positive or negative pressure (blowing or sucking respectively), or a combination of the two (Haug 1993). Where negative pressure is adopted (sucking air through the windrow), there is potential to process the air through a biofilter.

ASPs can be a cost-effective alternative to turned windrow systems – while there will be a moderate additional capital investment in the aeration floor / pipework and fan systems, there is usually reduced need for turning equipment and less land required for a given throughput as the process is more intense and shorter residence time.

Rosenfeld *et al.* (2004) conducted a pilot study of odour emissions from biosolids composting comparing a windrow process with an ASP followed by biofiltration. The compounds commonly responsible for odours in biosolids include ammonia, dimethyl disulfide, carbon disulfide, formic acid, acetic acid, and sulfur dioxide (or carbonyl sulfide). The concentrations of ammonia, formic acid, and acetic acid in the ASP were 72%, 57%, and 11% lower, respectively, compared to the turned windrow system, while dimethyl sulfide, carbon disulfide, and sulfur dioxide (or carbonyl sulfide) concentrations were below detection limits. Using dilution-to-threshold olfactometry, aeration followed by biofiltration was found to reduce the odour from biosolids composting by 98%. Biofiltration also altered the character of odour emissions, producing a less offensive odour with an earthy character. Biofiltration is commonly associated with forced aeration systems (though not always). This is discussed in more detail in Section 8.1.

Another interesting and potentially economical method of 'in vessel' forced-aeration composting involves the use of bag systems. Commercially available examples of these systems include the Ag-Bag (available internationally) and FABCOM from Australia. In this type of technology, the desired material is typically pushed into a plastic (polyethylene) sleeve while a perforated aeration pipe is laid on the bottom of the bag. Avidov *et al.* (2017) evaluated the Ag-Bag system for biosolids and green waste composting. They demonstrated effective process management of thermophilic conditions within the sleeves along with odour control. They suggested that composting could be managed with this system in two phases: firstly, a closed sleeve for 6–8 weeks during which odour is treated, and; secondly an open pile, at which time odour control is no longer necessary. Such systems are yet to experience widespread take-up.

2.3 Process control

The formation of odorous compounds is inherently associated with the decomposition of organic matter (Haug 1993; Epstein 1997). Odours *will* therefore form during composting even under "optimal conditions". Nevertheless, the failure to develop these optimal conditions is a guaranteed recipe for making matters worse and the nature and noxiousness of the odours will be worse under sub-optimal conditions. The focus in managing composting operations is therefore two-fold:

- Optimising process control to minimise the generation of odours, and
- Managing conditions to minimise the impact of odours as they form.

2.3.1 Feedstock receival

An important first step is to understand the risks associated with particular feedstock materials – whether they are related to odour causing potential, contaminants or any other issue. The facility's management must first determine whether a feedstock under consideration can be effectively handled, or whether it would negatively impact compost quality and the environment.

Every composting facility should have an established protocol for selecting potential new feedstocks, preferably before regulatory approval is even sought. This typically involves:

- Obtaining a sample of the feedstock from the generator and sending it away to a certified laboratory for testing. The testing provides basic information, for example of the C:N ratio and moisture content of the feedstock, but also of potential contaminants of concern.
- Retaining another sample and sealing it in a plastic bag to simulate the anaerobic decomposition process. The bag can be kept in a warm place for two to three days before it is opened by someone whose sense of smell has not been compromised by working at the composting facility. This person should give an indication of the intensity and hedonic tone (unpleasantness) of the smell. If objectionable odours are noticed, then the composting facility operator will know to be prepared to process the material promptly when it arrives.

Organic wastes are comprised of readily degradable, slowly degradable and non-biodegradable fractions of organic matter. Highly putrescible materials have especially high contents of the biodegradable organic matter fraction (or biodegradable volatile solids, BVS). BVS content has a pronounced effect on odour emissions. Zhang et al. (2009) found that peak odour concentrations and emission rates increased dramatically as the BVS increased in trials from 45% to 65%. Cumulative odour emissions over the course of composting therefore increased with BVS.

High-BVS feedstocks may degrade so quickly that they rapidly consume all available oxygen and become anoxic (Coker 2012), since oxygen is consumed faster than it can be replenished. But increasing the oxygen supply under these conditions may have little practical effect since too much air movement will physically strip odorous compounds from a mix before they can be oxidised into less offensive forms.

In practice, the solution to this issue is to blend and dilute high-BVS feedstocks (i.e. highly putrescible feedstocks) with slowly degradable materials such as green waste. Potentially odorous material must be combined in a mix as quickly as possible upon arrival at a composting facility. Very often, putrescible feedstock material arrives at a composting facility in an anaerobic condition, because it has been stored in a closed vessel for a period of time at the generator's premises. So it must be quickly combined with bulking agent to bring it to an aerobic condition and to begin the process of thermophilic composting but at a controlled rate. There are numerous other steps that can be taken in the materials receiving area to manage odorous feedstock (Table 1).

Table 1: Approaches to minimise and manage odorous feedstocks in the materials receiving area of composting facilities (Californian Integrated Waste Management Board, 2007)

Possible Cause	Management Approach
Materials arriving with odours	• Mix materials upon receipt (increase material porosity) • Stockpile bulking agent or high carbon amendments at receiving basin and ready for unexpected deliveries • Make smaller piles • Consider blanketing odorous materials with a thick layer of bulking agent or mature compost • Enclose the receiving floor • Aerate receiving floor • Add lime or wood ash to piles to adjust pH • Reject odorous loads if possible • Eliminate troublesome feedstocks • Incorporate wet or odorous loads directly into actively composting windrows
Material sitting too long prior to being processed or mixed	• Expedite material processing • Increase operating shifts • Reduce incoming throughput • Identify alternative outlets for incoming materials • First in, first out processing • Reduce size of material stockpiles • Increase collection frequency • Increase grinding/processing capacity (contract grinder/screener) • Consider blanketing odorous materials with a thick layer of bulking agent

Upon the introduction of a new feedstock to a composting facility, it is always advisable to conduct small-scale trials to assess the practical aspects of handling the new material and to monitor its performance in a composting pile. To begin with, new feedstocks should be added gradually to tried and trusted compost mixes, starting with small volumes (say 10% of the mix) before consideration is given to increasing its proportion in the mix.

2.3.2 Preparing the mix for composting

Best practice composting always starts with getting the mix right in the first instance. There are three main considerations with respect to mix preparation, *viz*. carbon to nitrogen or C:N ratio, moisture content and porosity. Each of these will be discussed in turn below.

The C:N ratio is the ratio of elemental carbon (C) to elemental nitrogen (N) by weight in organic material. The reported ideal ratio of C:N for thermophilic composting is generally thought to be in the range of 25 to 40 (Haug 1993; Epstein 1997). Getting the ratio of C:N in a compost mix right presupposes that the individual C:N ratio of each feedstock in a mix is known. Whilst some published tables of the characteristics of various feedstocks are available (e.g. Rynk 1992), they should be used only as a starting point in any investigation of potential feedstocks. As discussed earlier, samples of individual feedstocks should be sent to a laboratory for analysis. The 'hard data' from the laboratory analysis can then be used to calculate an ideal ratio of the feedstock in a mix, with respect to ratio of C:N but also moisture content and bulk density.

Where there are a number of feedstocks involved, calculating the C:N ratio of a proposed mix can be a daunting task for facility operators because each feedstock can have vastly different physicochemical characteristics. Fortunately, on-line calculators are available that simultaneously calculate the C:N ratio and moisture content of any proposed mix, provided that accurate physicochemical input data are used (e.g. Cornell Waste Management Institute[2]).

Rapid escalation of temperature should never be used as an excuse for failing to determine the physicochemical characteristics of a compost mix by laboratory analysis. Materials of both suboptimal C:N ratios as well as those of very high C:N ratios can heat up under some conditions. When composting high C:N ratio woody green waste, for example, an inexperienced operator may be deceived into believing that "all is well" just because high temperatures are achieved and maintained for long periods. High C:N ratios unnecessarily prolong the process of composting (Epstein 1997), putting pressure on facilities that quickly run out of space. Experience shows that stockpiling this type of material before it has finished composting increases the risk of odour and fire problems developing.

While high C:N ratios can delay the completion of composting, low C:N ratios can result in loss of nitrogen (N) as the odorous gas, ammonia. Some animal manures such as poultry litter can have very low C:N ratios, and the odour of ammonia is very noticeable. Piles of poultry litter will still heat up, despite having a low C:N ratio and being quite dry (Wilkinson et al. 2011), but the loss of N as ammonia is not only odorous but it also represents the loss of a valuable plant nutrient.

Degradation of proteins (high N) to either ammonia gas or ammonium salt is a pH-mediated reaction. Under conditions of high pH (above approximately pH 9), degradation of proteins in low C:N ratio materials (say under 15:1) is dominated by the ammonia gas pathway. In low pH conditions, VOCs are a particular problem. Acidic, low pH conditions are common on the initial phases of composting due to formation of organic acids (mostly acetic and lactic acids) and the pH will generally become more neutral as the compost matures. Acidic conditions can become problematic for waste streams such as food waste that contains meat (Sundberg et al. 2013).

[2] http://compost.css.cornell.edu/download.html

The ideal pH for most composting organisms and to prevent excessive pH-mediated reactions, is generally considered to be between pH 5.5 and 8.0[3]. The solution to the loss of ammonia is not necessarily in adjusting the pH directly, but rather in raising the C:N ratio of the mix in the first place.

The optimal moisture content for composting is typically thought to be around 50% (w/w) (Haug 1993; Epstein 1997). Some composting systems with forced aeration perform better at slightly higher moisture content – around 55%.

Organic matter decomposition takes place around the “biofilm” surrounding compost particles (Figure 2). This biofilm consists of a thin layer of water within which compost microorganisms do their work (Cao et al. 2013). At about 50% moisture content, the balance between free air and water between the compost particles is about right for aerobic bacteria to thrive. When moisture content exceeds 60%, the pore space between particles is filled with water, oxygen diffusion is impeded, and anaerobic microorganisms begin to dominate (Haug 1993; Epstein 1997). Anaerobic conditions exacerbate the risk of odorous gases forming in composting systems.

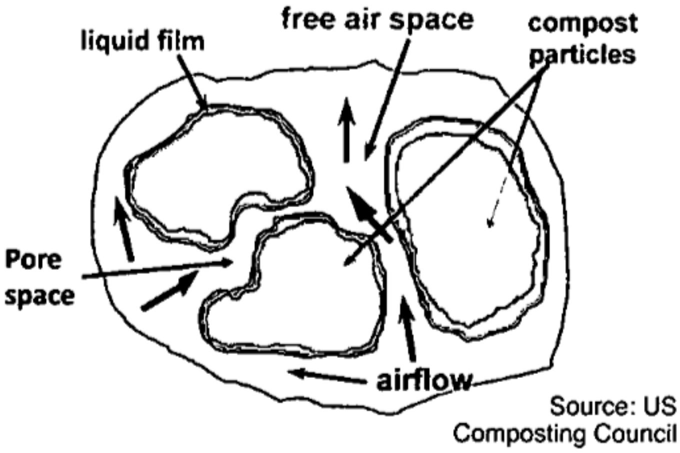

Figure 2: Relationship between water and free air space surrounding composting particles.

In preparing a mix, it can be difficult to balance the C:N ratio and moisture content in one hit. As a general rule, it is always better to try to achieve an optimal C:N ratio whilst erring on the side of a drier mix, for it is a lot more difficult to remove water from a mix without adversely raising the C:N ratio, than it is to add water.

The third issue we will consider here is the porosity of the mix. Air-filled porosity is the volume of free air space in a mix. Air-filled porosity should be maintained above 40% (v/v), and ideally in the 55-65% range to ensure that a compost pile is maintained in an aerobic condition (Coker 2012; Rosen et al. 2000).

Whilst it is possible to measure air-filled porosity simply with a bucket and scales (Rosen et al. 2000), bulk density (in kg/m^3) is typically used as a surrogate. This is because a linear relationship exists between air-filled porosity and bulk density (Agnew et al. 2003). Bulk density at the start of composting should be below about 650 kg/m^3 (Coker 2012).

The particle size distribution of a compost mix plays a major role in providing the balance between the minimum structural integrity of a pile (to avoid slumping), and adequate porosity. There must be a good combination of finer compost particles that provide energy for the microbes, and larger particles that provide structural support. A pile that is too coarse will not heat up or retain sufficient water. A pile that is too fine

[3] http://compost.css.cornell.edu/monitor/monitorph.html

rapidly becomes anaerobic because water cannot drain away and diffusion of oxygen into the pile is impeded.

Feedstock that is used to provide structure to a compost mix is often described as the “bulking agent”. A bulking agent breaks open wet, poorly structured organic materials like food waste, manure or biosolids. Bulking agent is typically derived from ground-up wood waste or green waste. It can sometimes be screened out at the end of the composting process if not decomposed and reintroduced again to prepare fresh mixes.

Compost facilities should have sufficient bulking agent on hand so that incoming feedstock can be brought to an aerobic condition as quickly as possible in order to limit the impact caused by fugitive odour emissions. If that is not possible, such feedstock should be covered with a thick layer (75 to 100 mm) of unscreened compost or woody grindings (Coker 2012).

The uniformity of mixing is an additional consideration. Potentially odorous feedstocks, like food waste, biosolids and some manures can form balls of anaerobic material, which should be broken up and distributed as evenly as possible throughout a pile. In turned windrow composting systems, this is achieved mainly during the thermophilic compost phase (see below). But in aerated static piles and in many in-vessel systems without mechanical agitation, feedstock must be mixed together as uniformly as possible prior to setting up for composting. This can be achieved, for example, with a batch-blending system containing blades and augurs.

2.3.3 Thermophilic composting phase

Once the mix has been prepared to the appropriate specifications of C:N ratio, moisture content and porosity, the active phase of composting can begin.

In most cases, the temperature in the interior of the compost pile should reach thermophilic conditions (above 45°C) within 24 to 36 hours of being set up. During this phase of composting, which usually lasts between 3 and 9 weeks, temperatures in the 60-65°C range are routinely reached. Pathogens and weeds seeds are best controlled above a temperature threshold of 55°C, while decomposition is maximised somewhere in the thermophilic region of 45°C to 60°C (Haug 1993; Epstein 1997).

During the thermophilic stage of composting, elevated temperatures result in an enormous increase in the rate of microbial metabolism, but high temperatures also increase the volatility of odorous compounds. The direct relationship between temperature and odorous emissions holds true from ambient to about 65°C (Day *et al.* 1999; Zhang *et al.* 2009). Odorous emissions begin to decrease above about 65-70°C, but so does microbial metabolism (Haug 1993; Epstein 1997), and so temperatures exceeding that level are generally avoided.

Scaglia *et al.* (2011) studied the relationship between microbial activity in compost and VOC degradation. Two distinct groupings of compounds were observed – those whose degradation showed a strong correlation with microbial activity (measured by biological stability testing), and those that did not. In the first group, concentrations of aliphatic hydrocarbons, ketones, alcohols and nitrides were reduced, showing a strong correlation with biological stability (with an r^2 ranging from 0.84-0.87). Terpenes also correlated well with DRI ($r^2 = 0.95$), but the researchers suggested that, probably, in this case, both biological degradation and stripping phenomena occurred.

The second group of compounds did not show strong reduction of their concentration with biological stability. These included the aromatic hydrocarbons, furans, and halogenated organic compounds (Scaglia et al. 2011). These molecules represent xenobiotic compounds (aromatic and halogenated compounds) or products (e.g. furans) of the thermal decomposition of other molecules (Ruther and Baltes, 1994). As no degradation of the emission concentration of these substances was observed and taking into consideration that concentration depends on the airflow rate used, Scaglia et al. (2011) deduced that degradation/stripping of these molecules occurred, at least, at a rate similar to that of airflow rate of sample taken at different biological stages.

Careful management is required to meet the various objectives of a successful composting operation. These include, but may not be limited to:

- Pathogen and weed-seed disinfestation ('pasteurisation'),
- The maintenance of composting in an aerobic state,
- Minimising both on-site and off-site environmental impacts, and
- Business objectives such as timely completion of composting (for cost control and to free up space).

The first step to achieving these objectives is to ensure that, as far as possible, the physicochemical properties of the starting mix have been optimised (as discussed above). Adequate preparation to circumvent potential hazards is the first key to success as it is often difficult to fully recover from problems once they have arisen.

Five percent (5%) oxygen content is generally considered to be the minimum threshold for 'aerobic' composting, though above 10% is preferable (Wilkinson *et al.* 1998). The maintenance of aerobic conditions and control of pathogens and weed seeds are somewhat co-dependent. The maintenance of aerobic conditions ensures that thermophilic conditions are reached and are maintained for sufficient duration to kill pathogens and weed seeds. However, too much airflow through a composting pile can rapidly cool and dry it out. Once thermophilic conditions are reached, substantially more airflow is typically needed for cooling a pile than for maintenance of aerobic conditions (Haug 1993).

The previous section discussed the importance of mix porosity to ensure that the compost contains sufficient free airspace and structural support to avoid slumping. However, even in a well-structured pile, oxygen is rapidly depleted at elevated temperatures through microbial metabolism – far more so than can be supplied through simple diffusion into the pile. For rapidly biodegradable mixes, air is therefore typically reintroduced into the pile by means of either physical agitation (mixing, turning), or by forced aeration, or by a combination of the two (Haug 1993; Epstein 1997).

Physical agitation (mixing, turning) provides numerous functions:

- It loosens or 'fluffs up' a compost pile, reducing the negative impact of compaction / settlement;
- It exposes compost particles to abrasive forces, opening up new surfaces that can be exploited by microbes, speeding up the progress of composting;
- It ensures that all compost particles are subjected to thermophilic conditions (when it is done properly and frequently enough); and
- It allows heat to escape from excessively hot compost piles.

The type of aeration strategy employed to achieve optimal conditions is feedstock dependent and site specific. A front-end loader may be sufficient for well-structured feedstock formed in windrows, like green waste. It may also still be sufficient for turning more odorous feedstocks, provided that sufficient buffer distances exist around the facility to allow adequate dispersion of odour into the atmosphere.

Forced aeration systems are typically used in aerated static piles/windrows, bay/bunker type systems, and in containerised systems such as in-vessel reactors (discussed in section 2.2.2). Although forced aeration systems theoretically have better prospects for odour control, they are not exempt from problems as noted above.

Operational considerations for turned windrow systems with respect to weather patterns are particularly critical for managing the impacts of odour generated during the thermophilic composting phase. Complaints occur when the odour that is inevitably generated does not effectively disperse into the atmosphere. Odours tend to accumulate under zero- or low-wind speed conditions. Furthermore, turbulent wind patterns disperse odours faster than laminar, or smooth, wind patterns (CIWMB 2007; Coker 2012). Odour dispersion is discussed in more detail in 6.1. Under minimal dispersion conditions, activities that might generate odours, such as feedstock mixing and windrow turning, should be avoided as much as possible without unduly constraining operations.

It was discussed previously the importance of getting the moisture content of the mix right to ensure optimal conditions exist for composting. During the thermophilic stage of composting, care must be taken to ensure that the compost does not dry out. Excessive fan speed in forced aeration systems and frequent turning in windrow systems can result in the loss of too much water during composting (Haug 1993; Epstein 1997). In hot, dry climates, keeping moisture levels up in composting piles can be a real challenge. In the tropics, wet season rainfall can result in a different challenge to manage – large volumes of water that must be effectively drained away in order to prevent odours forming in pools of water (or leachate) on the composting site.

Compost piles should not be moved to the next stage of an operation (maturation or curing) until the thermophilic stage of composting has been completed. Compliance with pasteurisation standards (exposure to at least 55°C for 3 days)[4] on its own does not constitute the completion of thermophilic composting – it is only part of the picture. This is an important point to consider since operators may be tempted to stockpile compost in large “curing” piles after the pasteurisation requirement has been met, especially when space is limited.

These materials may not have completed the thermophilic phase, and their continued composting in large piles can lead to odour issues and risk of fires developing. The elimination of compost stockpiles through effective marketing strategies should therefore be given equal priority to technological solutions for odour control.

It was noted earlier that the fact that a compost pile heats up rapidly is not necessarily an indication that the mix has been optimised. This is particularly relevant to green waste feedstock – it might heat up rapidly despite having a C:N ratio in excess of 40:1. This type of material may continue to compost for many months – long after pasteurisation standards have been met. To avoid this problem, operators should optimise the mix to ensure that the thermophilic stage of composting is completed as quickly as possible.

Figure 3 shows that the thermophilic phase of composting is not completed until maximum temperatures start declining below 45°C (this assumes that the composting process has been managed appropriately). At this point, the curing or maturation phase of composting can begin.

[4] These conditions could be reached within 5 days in in-vessel systems or within 15 days for windrow systems (including 3-5 turns)

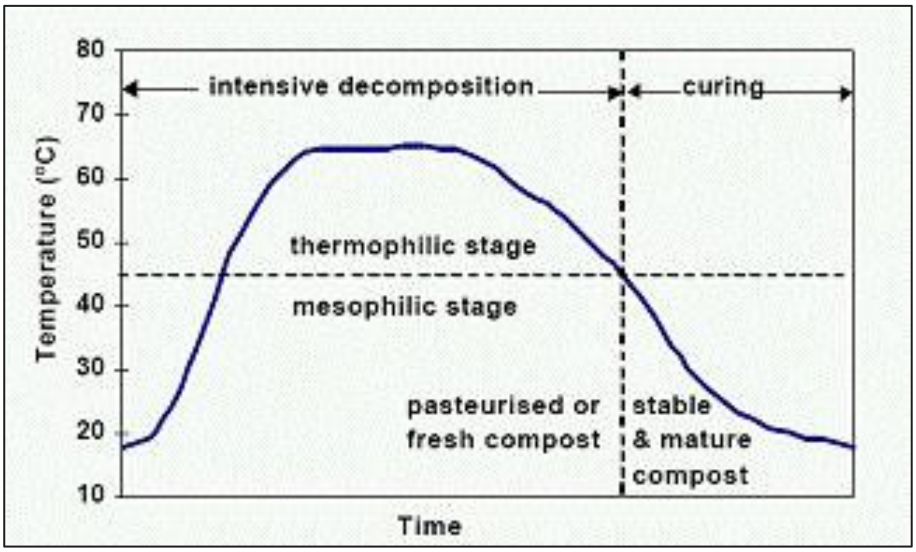

Figure 3 Phases of composting (Wilkinson et al, 1998)

2.3.4 Curing or maturation stage and screening

During this phase, the composting process continues to be managed, but less intensively so, and the potential for odour generation is greatly reduced. The early curing phase may still be characterised by the odd spike in temperature above 45°C, but there should be definite evidence that temperatures are on the decline. To avoid the possibility of odour problems, the same starting compost mix should be kept during the early phase of curing. Premature screening (removal of bulking agent and impurities) has the potential to cause immature compost to quickly become anaerobic as labile carbon continues to be consumed by microbial activity and as high temperatures resume.

During the latter stages of curing, the compost can be screened. Since screening reduces the air-filled porosity of compost, pile dimensions should be reduced to compensate[5]. Compost in the curing phase is typically turned less frequently, and the moisture content is allowed to fall to around 40% (Wilkinson *et al.* 1998). The curing phase can take 1 to 6 months, depending on the feedstock. It involves the slow decomposition of remaining labile carbon and is responsible for the stabilisation of compost products so that they can be safely stored or used to amend soil. During this phase, fungi begin to dominate while the more biologically resistant compounds are degraded, and humic substances are formed along with the build-up of nitrate nitrogen (NO_3-N) (Epstein, 1997).

The odour of cured compost should not be unpleasant – it should smell like freshly turned soil. It is also most suitable for use as a soil conditioner and should have useful quantities of available nutrients that will benefit plant growth (AS4454 2012).

In contrast, immature compost is more likely to have an unpleasant odour and become anaerobic when stockpiled. Under these conditions, odorous VOCs can develop, and if apply to soil, plant growth can be suppressed due to phytotoxicity or competition for nutrients (Wilkinson *et al.* 2009). Methane build-up under anaerobic conditions could contribute to the risk of fires, and gases trapped in bagged compost can lead to expansion and rupturing (Wichuk and McCartney 2010). Odours released

[5] Recommended dimensions vary with feedstock. As a guide, during thermophilic composting, green waste windrows are typically more than 2m in height and 4m at the base. After screening (during curing), these windrows should be reduced in size to about 1.5 m (height) by 2.5 m (base).

during continued decomposition of immature compost may also attract disease vectors (Ge *et al.* 2006).

2.3.5 Storage of finished compost

It is inevitable that finished compost needs to be stockpiled, especially during periods of soft market demand at due to seasonal demand profiles. However, the previous section highlights the importance of the curing phase to ensure that stored compost does not contribute to odour issues.

Assuming that compost is properly cured, it can be stored in large piles (within reason) for an indefinite period without causing any odour issues. It is prudent to keep stored compost under cover (a roof or tarp) to prevent cross-contamination with unfinished compost and the potential recolonisation of the cured compost with weed seeds, but this is not always practical on large sites.

Stability and maturity testing determine the storability of compost. Much research has been directed towards appropriate methods for determining compost stability and maturity (Lu *et al.* 2018; Wichuk and McCartney 2010). A range of test methods have been developed, but the most widely used and commonly accepted methods are based on respirometry (AS4454 2012). Respirometry assesses the level of biological activity in a sample under conditions conducive to microbial activity by measuring the rate of respiration in the form of carbon dioxide evolved or oxygen consumed, or in the form of heat generated by this biological activity.

Solvita™ is an example of a commercially available stability test. It does not require complex laboratory equipment – it can be performed on-site at most composting operations. It is used around the world, has been included as an acceptable test method in several European compost guidelines and regulations, including in Germany, Denmark, Sweden, Spain, and Norway (Wichuk and McCartney 2010). Solvita™ is also an acceptable test method in the Australian Standard (AS4454 2012). A 'Maturity Index' is determined from the combination of two tests in the Solvita™ kit – carbon dioxide (CO_2) evolution and ammonia (NH_3).[6] These tests can assist compost producers in determining when compost is mature enough to be safely stored.

Section 2 – key findings and recommendations

- Understanding the relationships between food source (feedstock), environmental conditions (e.g. temperature, air and water) and metabolic activity (microbial species, diversity and activity) is critical to successful operation of a composting process, including how odours are generated and managed.
- Odours will form during composting even under optimal conditions. Nevertheless, failure to maintain optimal conditions is highly likely to make matters worse and the nature and noxiousness of the odours will be worse under sub-optimal conditions.
- Olfactometry, or using the human sense of smell, remains as the industry and regulatory standard, and provides the best possible method currently available for odour evaluation.
- Getting the physicochemical composition of the feedstock mix right (i.e. optimal physical characteristics such as particle size and porosity plus optimal ratios of carbon, nitrogen and other nutrients) is the key to maintaining the consistent aerobic conditions necessary for low odour emissions, regardless of the composting system employed.

Windrow Turning

- Turning frequency has less impact on the composting process than other key process variables such as feedstock physicochemical characteristics, moisture content and

[6] Elevated CO_2 levels in compost indicate high rates of microbial activity (thus immature compost). High NH_3 is also an indicator of immaturity since more mineral nitrogen is converted into nitrate-N (NO_3-N) as the process of maturation advances.

Section 2 – key findings and recommendations

windrow size; but it can influence such things as the rate of decomposition, compost bulk density and porosity, and the time required to reach maturation.

- Turning a windrow in itself, has limited direct effect on maintaining aerobic conditions. Studies have shown that any oxygen which is introduced into a windrow during turning is generally consumed within hours.
- As such, the porosity of the composting materials is far more important, because it determines how freely fresh air can move through the pile. A degree of turning can help to improve porosity by loosening the materials and undoing the effects of compaction due to settlement, particularly in larger windrows, as well as redistributing moisture. The use of bulking agents such as green waste or wood chips at appropriate particle sizes and ratios, is critical to maintaining porosity and air flow in passively aerated windrows.
- On the other hand, care must be taken not to overwork or excessively turn a windrow. An aggressive turning schedule or method can reduce the porosity of a windrow by breaking down compost particles, which can reduce air flow and lead to anaerobic conditions.
- At the same time, turning also potentially assists the release of odorous gases that may have accumulated within the windrow voids. Research has shown that increased turning may increase the loss of ammonia gas, which is odorous and its loss also reduces the nutrient value of the compost product.
- Specialised turners are more effective at turning and mechanical agitation and generally more efficient in terms of labour and time, compared to generic plant such as front-end loaders or excavators. They are more effective at distributing moisture and breaking up anaerobic clumps that may form in some feedstocks. However, over-use of windrow turners may have an adverse effect and the more gentle action of a front-end loader may be beneficial for some feedstock mixes.

Recommendation - Turned Windrow Best Practice

- There is no best practice standard for the frequency and method of turning - turning methods and schedules need to be optimised for the feedstock mix and site requirements. This requires a balancing of the above factors by an experienced operator and potentially trials supported by site measurements to determine the optimal combination. That said, there are some common considerations:
  - Focus on adequate porosity - mix odorous materials with a generous and appropriate ratio of bulking material (e.g. shredded green waste) with particles that are not too small.
  - Identify the optimal turning method and frequency considering the compost mix and characteristics, supported by trials with site measurements
  - Minimise turning events for windrows containing odorous feedstocks, especially during the first 7-10 days of composting, with only the minimum turning required to support pasteurisation and moisture redistribution. This enables the odorous by-products generated during this initial phase to be oxidised to less odorous compounds before they are released to the atmosphere. The compounds will continue to decompose as they move through the windrow mass.
  - When turning with a front end loader, ensure that the operators do not drive up on the compost when windrows are being formed, which can cause compaction and reduce airflow.
  - Covering odorous windrows with a thick layer of matured (unscreened) compost has been shown to act as a biofilter for emissions from the windrow surface. Further detail on biofilters is covered in Section 8.1.

Enclosed and forced aeration systems

- Enclosed and forced aeration composting systems come in many forms but offer the potential of: more precise control over composting conditions; ensured continuous aerobic conditions; rapid pasteurisation and decomposition; and improved odour containment and control.
- Aeration rates need to be carefully controlled and balanced. Too much air will drive out heat and undermine pasteurisation, while it is also generally considered that increased

Section 2 – key findings and recommendations

rates of aeration result in a decrease in concentration of odorous compounds emitted, but an increase in total mass emissions. Operators need to determine the optimal aeration strategy for their particular compost mix through site trials and sampling in the commissioning phase.

- Aerated static piles (ASPs) are the simplest form of forced aeration system and can be a cost-effective alternative to turned windrow systems. While there will be a moderate additional capital investment in the aeration floor / pipework and fan systems, there is usually reduced need for turning equipment and less land required for a given throughput as the process is more intense.

Recommendation – composting systems

- Composting operations that process highly odorous materials and/or are located close to sensitive receptors should consider and assess the implementation of some form of forced aeration and/or enclosed composting process, for at least the initial phase of composting.
- Forced aeration strategies need to be optimised for a particular compost mix, so as not to have an adverse impact on odour emissions.

Feedstock Receival

- Highly putrescible feedstocks, which can be characterised by a high proportion of biodegradable volatile solids (BVS), often arrive at a composting facility in an anaerobic condition due to the time and way they have been stored by the waste generator. They also decompose rapidly in a composting environment and can quickly consume available oxygen. The solution to this issue is to blend and dilute highly putrescible or potentially odorous feedstocks with slowly degradable materials and bulking agents such as green waste in appropriate ratios to control the decomposition rate. Potentially odorous material must be combined in a mix as quickly as possible upon arrival at a composting facility.

Recommendations for Feedstock Receival

- Operators should:
  - Keep an ample stockpile of bulking agent or high carbon material at the receiving area to immediately mix with all deliveries of odorous materials
  - Immediately mix potentially odorous materials upon receipt and ensure that materials are mixed uniformly throughout
  - Consider enclosing the receival facilities for highly odorous materials and the initial mixing operation, with appropriate ventilation and biofilter systems
  - Consider blanketing odorous solid materials with a thick layer of bulking agent
  - Work with generators and collectors to increase collection frequency
  - Have a system in place to assess and reject unacceptably odorous materials and eliminate troublesome feedstock sources
  - Undertake small scale trials of new feedstocks prior to accepting full loads, to assess the practical aspects of handling the new material and to monitor its performance in a composting pile.

Process Control

- Preparing the right mix of feedstocks for composting is critical, with particular attention to C:N ratio, moisture content and porosity.
- The ideal C:N ratio for composting is in the range 25 to 40 and operators should understand and monitor the C and N content of their feedstocks, including lab analysis of samples as appropriate.
- Compost mixes outside the ideal range may still heat up and appear to be composting well. However, high C:N ratio mixes (low on nitrogen) will take longer to mature and increase the risk of odour formation in the curing piles. Low C:N ratio mixes (excessive nitrogen) can lead to loss of nitrogen as odorous ammonia gas.

Section 2 – key findings and recommendations

- The optimum moisture content for composting is considered to be around 50% but some forced aeration systems perform better at slightly higher moisture contents of 55%. Above 60%, the pore spaces in the compost are filled with water, impeding air flow and leading to anaerobic conditions.
- It is generally better to focus on achieving an optimal C:N ratio whilst erring on the side of a drier mix. It is easy to add water to a mix, but difficult to remove moisture.
- The porosity of the mix (the proportion of free air space in the voids) should be above 40% and ideally in the range 55-65%. Bulk density is often used as a surrogate for porosity (there is a linear relationship) and is easy to measure on site. Bulk density of the mix should be below 650 kg/m^3.
- The optimum pH level for most composting organisms is considered to be pH 5.5 to pH 8.0. Acidic conditions (low pH) are common in the initial phase of composting due to formation of organic acids but prolonged low pH conditions can lead to increased release of VOCs. High pH conditions can facilitate release of ammonia gas. The solution to managing pH levels is adjusting the C:N ratio of the initial mix, rather than direct adjustments, e.g. by adding lime.
- Temperature is an important (and relatively easy) parameter to monitor during the composting phase. The ideal range for thermophilic decomposition is around 45°C to 60°C, while 55°C is considered the minimum to achieve pasteurisation. Higher temperatures can increase the volatility of odorous compounds and there is a direct relationship between temperature and odour emissions up to around 65°C.
- Oxygen levels of 5% within the windrow voids is generally considered to be the minimum threshold for 'aerobic' composting, though above 10% is preferable.

Recommendations for Process Control

- Operators should have a clear procedure in place to ensure the initial compost mix is optimal in terms of C:N ratio, moisture and porosity. This should include testing and analysis of feedstocks to understand their physicochemical characteristics. Such testing need not be all the time for consistent feedstocks, but sufficient to understand the parameters and variability.
- Parameters such as temperature and pH should be regularly monitored throughout the composting process. Other parameters such as moisture content and oxygen levels may also be measured, particularly when processing wet or odorous feedstocks.

Curing

- The thermophilic phase of composting in a well-managed system is not completed until temperatures start to consistently decline below 45°C, at which point, the curing or maturation phase can begin.
- The curing phase is important and can take anywhere from 1 to 6 months. The smell of mature compost should not be unpleasant, while immature compost may have an unpleasant odour and become anaerobic when stockpiled.
- Compost should not be screened until the latter stages of curing, to maintain the compost porosity. Stockpiling of screened compost that is not fully cured can contribute to odour issues.
- There are a number of ways to test the maturity of compost including the Solvita™ test which can be performed on site and is considered an acceptable method in the Australian Standard AS4454 and several European guidelines.

Recommendations for Curing

- Compost piles should not be moved to the next stage of an operation (maturation or curing) until the thermophilic stage of composting has been completed.
- Maturity tests such as Solvita™ are widely accepted and can be done on site, to ensure compost is mature enough to be safely stored.

3 REGULATION OF COMPOSTING IN QUEENSLAND

Composting in Queensland is an environmentally relevant activity (ERA) meaning that composting facilities are regulated by the state and require an Environmental Authority to operate. Composting falls under ERA 53 which previously focused on composting but has been recently updated to include anaerobic digestion and is now entitled ‘Organic material processing’. This is part of a broader suite of waste-related ERA reforms which are being implemented – the change to ERA 53 commenced in November 2018. Changes to other waste ERAs will follow in July 2019.

The activities which fall under ERA 53 are defined in Schedule 2 of the *Environmental Protection Regulation 2008* and relate to processing, by composting or anaerobic digestion, organic material defined as:

(a) animal matter, including, for example, dead animals, animal remains and animal excreta; or

(b) plant matter, including, for example, bark, lawn clippings, leaves, mulch, pruning waste, sawdust, shavings, woodchip and other waste from forest products; or

(c) organic waste which includes

- *a substance used for manufacturing fertiliser for agricultural, horticultural or garden use*;*
- *animal manure;*
- *biosolids;*
- *cardboard and paper waste;*
- *fish processing waste;*
- *food and food processing waste;*
- *grease trap waste;*
- *green waste;*
- *poultry processing waste;*
- *waste generated from an abattoir;*

[* this category would seem to permit processing of wastes and residues from the manufacture of chemical fertilisers, which are typically inorganic chemicals.]

However, organic waste in this context does not include:

- *clinical or related waste;*
- *contaminated soil;*
- *quarantine waste; or*
- *synthetic substances, other than synthetic substances used for manufacturing fertiliser for agricultural, horticultural or garden use;*

There are exemptions from the need to be licensed under ERA 53 including facilities that process less than 200 tonnes per annum; production of mushroom growing substrate; and on-farm composting of agricultural and livestock waste (using materials sourced from that farm or provided free of charge from other farms).

There are no particular constraints on blending or co-processing inorganic materials that are not defined as wastes, unless the EA conditions of a particular facility ban certain materials (see below). Non-organic materials and regulated wastes cannot generally be processed under ERA 53 but may be permitted under a general ‘End of Waste’ provision approving the material as a resource and allowing its use under certain conditions. EoW codes have been published for the following materials which would allow their use in compost or blending with soils, under certain conditions:

- Coal seam gas drilling muds
- Fertiliser wash water
- Sugar mill by-products (filter mud, boiler ash)
- Foundry sand
- Coal combustion products

For those materials to be considered a resource rather than a waste, the generators and composting operators would need to comply with various requirements set out in the relevant EoW code, including contamination limits.

A small number of Queensland composting facilities are also licensed under ERA 55 - Regulated Waste Recycling or Reprocessing, which allows them to receive a range of Regulated Waste streams for processing via composting.

Each composting facility operates under an Environmental Authority that sets conditions around how the facility can operate. Appendix C provides a summary of key waste acceptance and odour control conditions in active composting licenses across Queensland.

Those conditions vary significantly, depending on the risk posed by the activities (e.g. facilities that also currently operate under ERA 55 - Regulated waste recycling or reprocessing, are considered higher risk and are more heavily conditioned) and the age of the approval. Older approvals tend to have more lax conditions than newer EAs, reflecting the fact that the technical understanding of the regulator has evolved over time and approaches have changed to suit current regulatory needs, the state of knowledge, and site-specific risks at the time of issue.

In conditioning a new or substantially modified EA to undertake composting under ERA 53, the regulator will reference the ERA 53 *Model Operating Conditions*[7] as the basis for new conditions, which have been published since 2014. The regulator can still apply other conditions to address specific risks associated with a particular site or operation, but the model conditions provide a framework to improve consistency going forward. With respect to odour, the model conditions include condition PMA001 (A1) which states:

> *"Other than as permitted within this environmental authority, odours or airborne contaminants must not cause environmental nuisance to any sensitive or commercial place."*

Other waste related ERA's have been amended through the *Environmental Protection (Waste ERA Framework) Amendment Regulation 2018*[8]. From July 2019, ERA 55 which currently covers recycling and reprocessing of Regulated Wastes, is being broadened to cover '*Other waste reprocessing or treatment*'. It will encompass reprocessing and treatment operations of both general and regulated wastes, which are not already covered by ERA 53 or another waste reprocessing ERA such as ERA 54 for *Mechanical waste reprocessing*, or ERA 61 for *Thermal waste reprocessing and treatment*. Arcadis understands the changes will not impact on conditions within existing EAs.

There are currently 96 facilities in Queensland licensed to undertake ERA 53 but a significant number of those are not actively engaged in composting operations. DES has identified 25 EAs which it believes are actively operating composting facilities. Arcadis has reviewed the key conditions within those licenses, particularly those

[7] https://environment.des.qld.gov.au/assets/documents/regulation/pr-co-composting.pdf
[8] https://www.legislation.qld.gov.au/view/html/asmade/sl-2018-0198#sec.18

pertaining to odour control and waste acceptance, which also has a significant bearing on odour potential.

3.1 Waste Acceptance

The waste acceptance conditions in each composting EA vary widely. Some EAs, generally the older ones, have no or very few specific waste acceptance conditions stated, which means that the operators rely on the materials identified in the definition of ERA 53 in Schedule 2 of the *Environmental Protection Regulation 2008* as noted above.

Most of the active composting EAs do specify a list of wastes that can be processed which is usually a subset of the list within the ERA 53 definition and may also include materials covered by a general EoW code such as coal ash.

Eight of the operators licensed under ERA 53 are also licensed to process some Regulated Wastes via composting under ERA 55. Such facilities are generally considered higher risk and operate under additional conditions. For example, most of the ERA 53 + 55 licenses will specify the wastes that *cannot* be processed (e.g. asbestos, clinical waste, general municipal waste, persistent organic compounds).

The license may also specify that any regulated wastes be analysed and must comply with contaminant thresholds specified within the EA and the license may include a condition along the lines '*Regulated waste that is not organic must not be used as feedstock in a ratio of greater than 1 part regulated waste to every 3 parts other material (dry weight).*' Many will also include a statement such as:

> *Wastes can only be accepted and used as feedstock if a risk assessment demonstrates all of the following requirements:*
>
> *The waste is homogeneous.*
>
> *The waste has characteristics or constituents that provide an agronomic or soil conditioning benefit to the finished compost product, and does not constitute mere dilution of the waste and its constituents into the product.*
>
> *The waste does not have any characteristics or constituents that adversely affect the composting process.*
>
> *Potential risks from receiving and handling the waste on the site and use of the final products that include the waste have been identified and determined not to present a risk of causing environmental harm.*

The key finding from the above analysis is there is substantial variation in the degree of conditioning and restrictions on waste acceptance between composting facilities across Queensland, which is a common theme for all EA conditions.

3.2 Conditions Aimed at Controlling Odour Emissions

The primary condition used in EAs to regulate odour emissions from a composting facility varies in form and wording, but is generally similar to:

> *Odours or airborne contaminants must not cause environmental nuisance to any sensitive or commercial place.*

Or

> *The release of noxious or offensive odours or any other noxious or offensive airborne contaminants resulting from the activity must not cause a nuisance at any odour sensitive place.*

An environmental nuisance is defined in the Environmental Protection Act as:

> *unreasonable interference (or likely interference) with an environmental value caused by*

- *aerosols, fumes, light, noise, odour, particles or smoke;*
- *unhealthy, offensive or unsightly conditions caused by contamination; or*
- *another way prescribed by regulation*

In some EAs the location where nuisance must be avoided is defined as any *'nuisance sensitive or commercial place'.* In other instances, nuisance cannot occur *'at or beyond the boundary of the approved place'*.

A sensitive place is typically defined within the EA as:

- a dwelling, residential allotment, mobile home or caravan park, residential marina or other residential
- a motel, hotel or hostel
- a kindergarten, school, university or other educational institution
- a medical centre or hospital
- a protected area under the *Nature Conservation Act 1992*, the *Marine Parks Act 2004* or a World Heritage Area

One EA emphasised the aspect of 'unreasonableness' and public safety, prohibiting release of odour that was *'unreasonably disruptive to public amenity or safety'.*

The likelihood of the activity causing a nuisance is also considered, with some licenses stating that the activity *'must not cause, or be likely to cause, a nuisance …'.*

The conditions noted above are generally outcome based – the expected outcome is stated (e.g. no environmental nuisance at a sensitive place) but it is up to the operator to determine how they will achieve that outcome. That approach is generally favoured by industry and works well where the outcome is measurable and can be readily linked back to that specific operation, but odour nuisance is often not in that category. Where there are multiple sources of odour within an area, it can be challenging to attribute an odour issue to a particular site and such conditions become very difficult to enforce, as has been the experience in the Swanbank precinct near Ipswich.

Licenses for newer facilities may also include conditions which seek to mitigate the potential for odour emissions by specifying operational measures to minimise odour formation and release. Such conditions attempt to address the cause of odours in composting and while there is a fine balance between prescriptive conditioning of the operation and managing the environmental impacts, such approaches may be more effective in the specific case of odour nuisance.

An example condition of that type is:

> *The holder of this approval must undertake all reasonable and practicable measures to minimise odour emissions to the atmosphere from the composting operations. Such measures should include:*
>
> *a) composting windrow forming and turning and compost windrow remixing operations in calm weather conditions where prevailing winds are not blowing in the direction of nuisance sensitive places;*
>
> *b) maintenance of any composting windrows and raw material stockpiles in moist conditions;*
>
> *c) minimisation of the storage time of odorous materials on the site;*
>
> *d) not allowing composting windrows to turn anaerobic;*
>
> *e) minimising the storage time of materials that may turn anaerobic;*
>
> *f) ensuring raw materials and the finished compost product are kept at an oxidised state;*

> g) *monitoring and maintaining the optimal Carbon to Nitrogen ratio and;*
>
> h) *monitoring and maintaining the optimal temperature in the composting windrows."*

Other conditions may require that compost additives with the potential to cause offensive odour must be immediately mixed with other composting materials and formed into windrows or covered with green waste or compost on the day they are received on site.

Such conditions should supplement and support the outcome-based, primary odour control conditions in an EA, rather than replace them. They would drive the operator to ensure that appropriate operational management procedures are in place and give the regulator an opportunity to take action when those procedures are not implemented, which may be easier to prove in some cases than linking an odour event to a particular operator.

Complaints management is also addressed in some EAs. A typical condition of this type states:

> *The person undertaking the activity to which this approval relates must investigate, or commission the investigation of, any complaints of nuisance caused by noxious or offensive odours upon receipt, or upon referral of a complaint received by the administering authority and, if those complaints are validated, make reasonable adjustments to processes or equipment to prevent a recurrence of odour nuisance."*

The composting facility is normally required to record all complaints received.

Controlling odour from leachate is also addressed in some cases as illustrated by the following two conditions:

> *The application of liquid compost additives should be applied so as to keep to a practical minimum the release of excessive amounts of leachate from the compost stockpiles and windrows which may cause a noxious or offensive odour at any odour sensitive place. Pooling of leachate from the use of liquid additives should be kept to a practical minimum.*
>
> *The settling pond used for the collection of contaminated stormwater and leachate must be maintained so as to keep to a practical minimum the release of a noxious or offensive odour from the licensed site to any odour sensitive place.*

In one circumstance the license highlights the potential for odour monitoring be conducted.

> *The person undertaking the activity to which this approval relates must, if directed in writing by the administering authority, undertake or commission the undertaking of odour monitoring for contaminants released from the approved place and places relevant to ascertaining the level, nature and source of odour nuisance at the affected premises.*

In reviewing conditions within environmental authorities, it is clear that individual sites have very different odour related conditions, with even the wording of the standard nuisance condition varying across facilities.

It would be appropriate to develop standard approaches to determining environmental nuisance for an existing site. This is currently defined in a subjective manner as it relies on whether the perceived odour is “unreasonable” or not. A test for nuisance odour would ideally reflect all of the relevant dimensions of odour which can be described by the FIDOL factors (Frequency, Intensity, Duration, Offensiveness, Location) which are discussed further in Section 5.2 below. It would also contain multiple site-specific criteria for assessment. Odour nuisance in particular could therefore be defined in a defensible and repeatable manner, with the nuisance state being triggered by extreme values of any FIDOL factor, or by pre-defined combinations of factors.

For example, frequently occurring odour of a low perceived intensity may be considered to be a nuisance. Similarly, infrequent odours at high intensity or with an offensive character could also be considered to be an environmental nuisance. The level of nuisance would be modified depending on odour duration. A fleeting odour would not be considered to be a nuisance, but a constantly perceivable odour may.

These criteria would be specifically defined, following a standard approach, for individual existing composting premises. It would not be appropriate to rely on a uniform set of tests for nuisance, as the changing of a single FIDOL factor, such as odour character can radically alter its nuisance effect. Site-specific criteria could then be applied at sensitive receptor locations, and when dealing with environmental complaints or incidents. They could be adjusted for use at the site boundary and onsite by facility staff to avoid nuisance events.

Chapter 9 provides further discussion around odour regulation approaches in Queensland and in other jurisdictions. Other jurisdictions such as New South Wales and Victoria tend to have the outcome based conditions, such as no odour at the boundary or impact on sensitive receptors, but they also have more prescriptive guidelines and regulations around locating composting facilities and applying technologies and control measures which are appropriate to the feedstocks being processed.

From the comparison of Queensland facility EA conditions discussed above, it seems that there would be benefit in supplementing the outcome based odour nuisance conditions by incorporating conditions which address the operational factors that lead to odour emissions – for example, feedstock storage and blending; windrow mixing and turning; maintaining aerobic conditions; and monitoring of key process parameters. These could be worded in a way that still provides flexibility and scope for operators to implement the measures in a way that suits their operation, but failure to implement those procedures would give the regulator an avenue to take action which will address the cause of the problems, even if it is difficult to establish a link between that operation and an odour event.

Section 3 – key findings and recommendations

- Waste acceptance conditions in existing EAs vary widely with some licences having no or very few specific waste acceptance conditions stated. Similarly, there is inconsistency in the conditions that are intended to control odour impacts. Inconsistency in regulation between otherwise similar sites creates an un-level playing field commercially (real or perceived) which may be a barrier to investment in upgrades and improvements.
- Most EAs require an outcome of no odour nuisance at any sensitive place. Such outcome-based conditions place the onus on the operator to determine the best way to achieve that outcome. The challenge with this approach is that the outcome can be difficult to measure and if there are multiple potential sources of odour around a ‘sensitive place’, it can be difficult to link a nuisance issue to a specific activity or operator and enforce these types of conditions.

Recommendations – EA conditions

- DES should explore options to harmonise waste acceptance conditions for existing composting facilities, including requirements around testing and assessing incoming feedstocks to understand their odour potential and impact on the process. There may be cases where there is a clear need to place additional or alternate waste acceptance conditions on a particular operator but a general consistent baseline should be achievable.
- DES should consider more widespread adoption of conditions which address the operational factors that lead to odour emissions – for example, feedstock storage and

Section 3 – key findings and recommendations
blending; windrow mixing and turning; maintaining aerobic conditions; and monitoring of key process parameters. These could be worded in a way that still provides flexibility and scope for operators to implement the measures in a way that suits their operation, but failure to implement or follow those procedures would give the regulator an avenue to take action which will address the cause of the problems, even if it is difficult to establish a link between that operation and an odour event.

4 ODOUR POTENTIAL OF COMPOSTING FEEDSTOCKS IN QUEENSLAND

As discussed in Chapter 1.3, particularly 2.3, odour generation in a composting process is a function of many factors but one of the most significant is the feedstocks, their composition and mixing ratios.

Arcadis has reviewed data from a number of sources to gain an understanding of the feedstocks that are currently processed by composters across Queensland, including:

- Feedstock data provided by DES,
- Waste acceptance criteria stated in licenses (relevant to composting) and in ERA 53 definition, and
- A feedstock list kindly provided to Arcadis by a major Queensland composter.

Based on these datasets, Arcadis has compiled a list of feedstocks known or thought to be used in composting, which is presented in Table 2 overleaf.

The list is long with over 100 feedstocks identified. To aid analysis, Arcadis has broadly categorised each material by:

- Whether it is organic or inorganic (according to the definition in ERA 53, see Chapter 3 – note ERA 53 permits processing of wastes and residues from the manufacture of chemical fertilisers as 'organic' even though most are typically inorganic chemicals). In some cases, there is insufficient information in the feedstock name to categorise, in which case it has been marked 'unknown'.
- Whether it is likely to be in solid, liquid or slurry form
- An assumed primary source category – e.g. industrial, animal matter, food processing

In addition, Table 2 includes a brief summary of 'odour factors' relevant to each feedstock (see below) and a rating by Arcadis of their potential odour contribution in a composting process based on the likely nature, state and chemical components.

The rating of potential odour contribution is high level, qualitative and somewhat subjective, reflecting the limited data available on most feedstocks. The key factors which have been considered are detailed below. The potential for an individual material to cause an odour issue is also a function of operational aspects such as blending rates with other materials, so it is difficult to apply generic classifications that cover all situations.

Nevertheless, feedstocks have been rated as having a low, medium, high or very high potential odour contribution. In assessing potential odour contribution, the following risk factors were considered:

- Feedstocks which are highly putrescible (a high proportion of readily biodegradable solids) are at higher risk of going anaerobic or being anaerobic upon delivery, and releasing odours during the initial rapid decomposition phase. They are therefore considered to pose a higher risk of odour generation.
- It is assumed that liquid or wet feedstocks would be adequately blended with green waste or other materials to balance the moisture levels, so being a liquid or having high moisture content in itself does not correlate to high potential odour contribution.
- However, feedstocks which are wet and putrescible are at risk of being in an anaerobic state upon arrival, and therefore higher risk of being odorous during the delivery, storage and initial mixing phases.

- Feedstocks which contain high concentrations of nitrogen compounds (such as food, proteins, animal waste, manure, biosolids, grass clippings) are assumed to present a risk of producing ammonia gas during composting and therefore higher risk.
- Feedstocks which contain high concentrations of sulfur or sulfurous compounds (such as food waste, paper, gypsum, manure and biosolids) are a risk of producing hydrogen sulfide during composting (under anaerobic conditions) and therefore higher risk.
- Feedstocks which contain proteins, fats and oils are a risk of producing volatile nitrogen and sulfur compounds, as well as VOCs, during composting and are considered higher risk.

The overall potential odour contribution rating takes into account the potential cumulative impacts of these factors, where a feedstock has multiple risk factors. For example, animal processing wastes can be expected to be high in proteins and fats, high in nitrogen, high in readily biodegradable solids and high in moisture content. They are likely to arrive on site in an anaerobic state, hence they have been categorised as very high potential odour contribution.

For materials which are effectively inert and very unlikely to make any contribution to odour (e.g. ash), the potential odour contribution is noted as ‘none’.

The table also includes notes about the nature (or assumed nature) of some feedstocks where this is not obvious from the product name.

Table 2: Summary and categorisation of composting feedstocks, including odour potential

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
Animal Matter	Abattoir waste	Organic	Solid	- decomposing meat and fat content, high protein - wet and high nitrogen content - decomposing meat / fat content - potentially anaerobic on arrival	Very high	
	Animal manures, including livestock manure	Organic	Solid	- wet and high nitrogen content - potentially anaerobic on arrival	High	
	Animal processing Waste	Organic	Solid	- wet and high nitrogen content - decomposing meat / fat content, high protein - potentially anaerobic on arrival	Very high	
	Animal Waste, including egg waste and milk waste	Organic	Liquid	- high fat and protein content -wet and likely anaerobic on arrival	Very high	
	Hide curing effluent	Organic	Liquid	- decomposing meat and fat content, high protein - potentially anaerobic on arrival	Very high	Assumed residues from the various steps in preparing animal hide including washing for removal of hair, fat and chemicals. Curing hides requires large amounts of salt.
	Paunch material	Organic	solid	- partially digested / fermented grass - wet and high nitrogen content - likely anaerobic on arrival	High	Partially digested gut contents of slaughtered animals
	Tallow Waste	Organic	Solid	- high fat and protein content - likely anaerobic on arrival	Very high	

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
Chemical	Ammonium Nitrate	Organic*	Solid	- soluble ammonium form - potential release of ammonia vapour during composting - assume this is in concentrated form (e.g. spoiled product)	High	A salt of ammonia and nitric acid, that is widely used in chemical fertilisers. It is highly soluble in water. ** Likely synthetic but fits the DES definition of organic under 'a substance used for manufacturing fertiliser for agricultural, horticultural or garden use'*
	Dewatered fertiliser sludge	Organic*	Slurry	- unknown composition, may contain volatile ammonia - assume this is in concentrated form (e.g. spoiled fertiliser product)	High	Assumed chemical fertiliser residue. ** Likely synthetic but fits the DES definition of organic under 'a substance used for manufacturing fertiliser for agricultural, horticultural or garden use'*
	Fertiliser water and fertiliser washings	Organic*	Liquid	- may contain volatile ammonia, assume dilute	Medium	Subject to an EoW code for fertiliser wash water - derived from cleaning or washing or fertiliser plant or hygroscopic absorption of moisture into fertiliser products. ** Likely synthetic but fits the DES definition of organic under 'a substance used for manufacturing fertiliser for agricultural, horticultural or garden use'*

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
	Filter/ion exchange resin backwash waters	Inorganic	Liquid	- unknown composition / source - assume organic content	Medium	
	Pot ash	Organic*	Solid	- Minimal, assume inert	None	Chemical fertiliser salts / minerals containing potassium ** Likely synthetic but fits the DES definition of organic under 'a substance used for manufacturing fertiliser for agricultural, horticultural or garden use'*
Food	Food Organics	Organic	Solid	- may contain meat / fat - high moisture / nitrogen - likely anaerobic on arrival	High	
	Organics extracted from mixed household waste / MSW	Organic	Solid	- may contain meat / fat - high moisture / nitrogen - likely anaerobic on arrival	Very high	Currently only applies to one facility (Cairns AWT plant), organic fraction mechanically separated from mixed waste
	Quarantine waste treated by an AQIS approved facility	Inorganic	Solid	- potentially contains meat / food	High	Assume mostly food and organic if coming to composters *Excluded from list of acceptable organic materials by DES*
Food processing	Beer	Organic	Liquid	- wet, potentially anaerobic?	Medium	Assume waste beer, spoiled / non-compliant product
	Brewery effluent	Organic	Liquid	- wet, commonly accepted in anaerobic state	High	
	Food processing effluent and solids	Organic	Liquid	- wet / high nitrogen - likely anaerobic on arrival	Very high	

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
				- potential meat and dairy contents		
	Food processing treatment tank or treatment pit liquids, solids or sludges	Organic	Slurry	- wet / high nitrogen - likely anaerobic on arrival - potential meat and dairy contents	Very high	
	Grain Waste	Organic	Solid	- assume dry, high carbon - potentially fermented?	Low	Assume mostly hulls / waste grains
	Grease trap - treated grease trap waters and dewatered grease trap sludge	Organic	Liquid	- wet, food and grease content - likely anaerobic on arrival	Very High	Mostly water - contains grease, oil, food and potentially cleaning products?
	Grease trap waste	Organic	Solid	- wet, food and grease content - likely anaerobic on arrival	Very High	Mostly water - contains grease, oil, food and potentially cleaning products?
	Molasses Waste	Organic	Liquid	- highly biodegradable - potentially anaerobic on arrival?	Low	
Food processing	Soft Drink Waste	Organic	Liquid	- assume high sugar content	Low	
	Starch Water Waste	Organic	Liquid	- high starch / sugar content	Low	
	Sugar and sugar solutions	Organic	Liquid	- assume high sugar content	Low	
	Vegetable oil wastes and starches	Organic	Liquid	- high carbon - wet, could be anaerobic on arrival	Medium	
	Vegetable waste	Organic	Solid	- high nitrogen / moisture	Medium	
	Yeast Waste	Organic	Solid	- fermented, yeast odour - potentially anaerobic	Medium	
Industrial	Amorphous silica sludge	Inorganic	Solid	- none, assumed inert	None	Cementitious additive?

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
	Ash	Inorganic	Solid	- none, inert	None	See EoW code for Coal Combustion Products
	Bauxite sludge	Inorganic	Solid	- none, in	None	Maybe highly alkaline containing iron oxide and other metals
	Carbon Pellets	Organic	Solid	- assume dry and stable, so low but depends on usage	Low	Assume derived from plant matter, likely to have been used as water or air filtration so composition will depend on previous use
	Cement Slurry	Inorganic	Slurry	- none, inert	None	
	Coal ash	Inorganic	Solid	- none, inert	None	See EoW code for Coal Combustion Products
	Compostable PLA plastics	Inorganic	Solid	- none, assumed inert	None	Biodegradable under optimal conditions
	Coolant Waste	Inorganic	Liquid	- volatile alcohols	Low	Mix of water and glycol (usually ethylene or propylene based), which picks up heavy-metal contamination
	Dye Waste (water based)	Inorganic	Liquid	- assume none	None	
Industrial	Filter cake and presses	Unknown	Solid	- unknown composition / source - assume organic content	Medium	
	Fly ash	Inorganic	Solid	- none, inert	None	See EoW code for Coal Combustion Products
	Foundry sands	Inorganic	Solid	- should be inert	None	See EoW code for Foundry sand. May contain phenol, used for setting the sand moulds

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
	Paint Wash	Inorganic	Liquid	- minimal assuming water based	Low	
	Paper mulch	Organic	Solid	- high carbon content, assume relatively dry	Low	
	Paper pulp effluent	Organic	Liquid	- depends on process - may contains sulphate, chlorine?	Medium	Composition will depend on source process but may contain fibres, calcium carbonates, clays, high BOD / COD - assume not highly concentrated black liquor?
	Paper sludge dewatered	Organic	slurry	- depends on process - assume mostly fibres - may contains sulphate, chlorine?	Medium	
	Plaster board	Inorganic	Solid	- sulphate content	Medium	
	Polymer Water	Inorganic	Liquid	- unknown content / source	Low	Possibly water absorbing polymers? Composition will depend on previous use
	Process Fluid	Unknown	Liquid	- unknown content / source	Low	Unknown source sector?
	Total Petroleum Hydrocarbon Water	Inorganic	Liquid	- VOCs / light hydrocarbons	Medium	Could include a wide range of hydrocarbons - most will biodegrade in optimal conditions, or evaporate, but some may be toxic to composting organisms in high concentrations
	Water based inks	Inorganic	Liquid	- assume none	None	

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
Industrial	Water based paints	Inorganic	Liquid	- assume none	None	Pigments include various metals and minerals (eg White: Titanium dioxide (TiO_2); Black: carbon; Blue copper calcium silicate; Red: cadmium sulfide). Binder may be Latex, vinyl (Polyvinyl Chloride), acrylic, Poly Vinyl Alcohol (made from the hydrolysis of polyvinyl acetate and is the most common binder in water-based paint - PVA can generally be regarded as a biologically degradable synthetic polymer, but aerobic / moisture conditions need to be optimal). Latex should be natural form. Acrylic and PVC not biodegradable. Other additives: - Propionic acid (prevents mould) - Silicone (waterproofing) Release fewer VOC's than oil-based paints
	Water blasting wash waters	Unknown	Liquid	- unknown content / source	Low	
	Water based glue	Inorganic	Solid	- assume none	None	
	Water based Lacquer Waste	Inorganic	Liquid	- assume none	None	

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
	Wood molasses	Organic	Solid	- potential VOCs / ammonia, acidic	Medium	Results from a process that transforms the wood cellulose into sugars (glucose). Usually involves the pyrolysis of wood using high temperatures and pressures with acids and then cooled and neutralised with lime. It is being used quite a bit in animal food (mixed with Urea) and agriculture as a soil improver (use on crops and pasture).
Plant matter	Cane residues	Organic	Solid	- high carbon	Low	Assume this is bagasse from sugarcane processing, may also include cane trimmings from harvest
	Cypress chip	Organic	Solid	- high carbon	Low	
	Forest mulch	Organic	Solid	- high carbon	Low	
	GPT Waste	Organic	Solid	- mostly vegetation and sludge, wet	Low	Gross pollutant traps - will be mostly leaves and organic debris with some litter
	Green waste	Organic	Solid	- moisture content will vary - potentially moderate nitrogen (grass) - depends on age / storage	Low	Mostly from domestic sources and commercial gardeners, composition will vary throughout the year

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
	Mill mud	Organic	Solid	- organic / sugar content - moderate nutrient content	Low	See EoW code for sugar mill by-products. By-product from sugarcane processing, contains filter mud from clarification of cane juice plus ash, potentially some lime
	Mushroom compost (substrate)	Organic	Solid	- assume composted but not mature - composting odours	Medium	
	Natural textiles	Organic	Solid	- assume dry and stable	None	
	Pine bark	Organic	Solid	- high carbon	Low	
	Sawmill residues (inc. sawdust, bark, wood chip, shavings etc.)	Organic	Solid	- high carbon	Low	
	Tub ground mulch	Organic	Solid	- high carbon	Low	Assume from clean virgin sources (forestry waste, land clearing)
	Wood chip	Organic	Solid	- high carbon	Low	Assume from clean virgin sources (forestry waste, land clearing)
	Treated Timber**	Organic	Solid	- High carbon	Low	Preservation chemicals include; copper chromium arsenic (CCA), creosote, alkaline copper quaternary and methyl bromide. Not acceptable in composting but has been composted previously, either deliberately or otherwise. Harmful to composting organisms and more

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
						resistant to decomposition
	Wood waste – clean (excluding chemically treated timber)	Organic	Solid	- high carbon	Low	Assumed to include untreated pallets, offcuts, boards, stumps and logs
	Worm castings suitable for unrestricted use	Organic	Solid	- assume mostly matured	Low	
Sewage & STP residues	Activated sludge and lime sludge from wastewater treatment plants	Organic	Slurry	- biomass from sewage treatment - wet and likely anaerobic on arrival	High	Assume from sewage treatment but may also be from industrial WWTP
	Biosolids	Organic	Slurry	- high moisture and nitrogen content - potentially anaerobic depending on storage	Medium	See EoW approval for Biosolids Odour risk will depend on level of prior stabilisation (could be high risk in some cases)
	Nightsoil	Organic	slurry	- from sewage / septic tanks - high organic / nitrogen content - likely anaerobic	Very high	
	Septic wastes	Organic	Slurry	- from sewage / septic tanks / raw sewage from portaloos - high organic / nitrogen content - likely anaerobic	Very high	
	Sewage sludge	Organic	Slurry	- from sewage treatment - high organic / nitrogen content - likely anaerobic	Very high	
	Sewage treatment tank or treatment pit liquids, solids or sludges	Organic	Slurry	- from sewage treatment - high organic / nitrogen content - likely anaerobic	Very high	

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
Soils and additives	Acid Sulphate Sludge	Inorganic	Slurry	- sulphide content	High	Contains iron-sulphide. Can be acidic and cause the dissolution / release of mineral metals (iron, aluminium, other heavy metals, arsenic)
	Bentonite	Inorganic	Solid	- none, inert	None	Assume from drilling muds but can also be found in paints, in the manufacturing of paper and is used as a water softener
	Crusher dust	Inorganic	Solid	- none, inert	None	
	Drilling Mud / Slurry (Coal Seam Gas)	Inorganic	Slurry	- assume mostly inert but contains hydrocarbons, lubricants and a high level of salt - some may contain sulphate compounds although the draft EoW requires drill muds to be free from detectable offensive odours	Low	See EoW approval for CSG rill Muds
	Gypsum	Inorganic	Solid	- sulphate content	Medium	
	Lime	Organic	Liquid	- none, inert	None	
	Lime Slurry	Organic	Slurry	- none, inert	None	
	Mud and Dirt Waste	Inorganic	Slurry	- assume inert, none	None	Assuming this is clean
	Sand	Inorganic	Solid	- none, inert	None	
	Soil	Inorganic	Solid	- assume inert	None	
	Soil treated by indirect thermal desorption	Inorganic	Solid	- assume inert	None	
Wastewater	Bilge waters	Organic	Liquid	- potential hydrocarbon / oil vapours - Assume saline composition	Low	Assume this is from ship pump outs, mixture of fresh and sea water, oil,

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
						sludge and other chemicals.
	Boiler blow down water	Inorganic	Liquid	- none, inert	None	Likely to contain mineral scale, solids - potentially treatment chemicals
	Brine Water	Inorganic	Liquid	- assume no organic content, so minimal	None	Composition will depend on source but assume saline
	Calcium Water	Inorganic	Liquid	- assume no organic content, so minimal	None	
	Car Wash Mud & Sludge	Inorganic	Slurry	- assume low	Low	Assume contains detergents (may or may not be biodegradable) and soil
	Carpet cleaning wash waters	Inorganic	Liquid	- VOCs, high pH	Low	Likely contains highly alkaline chemicals and chemical enzymes, high levels of VOCs, disinfectants, high concentrations of sodium bicarbonate, sodium citrate, sodium silicate or sodium phosphate, dyes, polymers, bleachers, esters, forms of butyl, dirt, soap, oil, grease, a variety of solvents, esters and other toxic chemicals, including PFAS (potential)
	Effluent Waste	Unknown	Liquid	- unknown composition / source	Medium	
	Forecourt Water	Inorganic	Liquid	- VOCs / light hydrocarbons - likely very dilute	Low	Assume petrol station forecourts, likely light hydrocarbon pollution
	Ground Water	Organic	Liquid	- unknown content, but should be inert	Low	

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
	Latex Washing	Inorganic	Liquid	- assume dilute, natural rubber	Low	
	Leachate Waste	Organic	Liquid	- likely high ammonia, sulphides, methane - will be anaerobic	Very high	
Wastewater	Low level organically contaminated stormwaters or groundwaters	Unknown	Liquid	- unknown content, but should be inert	Low	
	Muddy Water	Inorganic	Liquid	- assume inert, none	None	
	Oily Water	Inorganic	Liquid	- VOCs / hydrocarbons	Low	
	Soapy water	Inorganic	Liquid	- assume low	Low	
	Stormwater Waste	Unknown	Liquid	- unknown content / source sites	Low	Usually from bunds, which can't be directly discharged – unknown contaminants as will depend on source site
	Sullage waste (greywater)	Inorganic	Liquid	- may contain food / organics - potentially anaerobic on arrival	Low	Greywater from households (sinks, baths, showers), but not waste liquid or from toilets - likely to contain soap, soil, chemicals, detergents, bleaches, lint, food particles
	Treatment tank sludges and residues	Unknown	Slurry	- unknown content / source - could be high organics / anaerobic	High	
	Vehicle wash down waters	Unknown	Liquid	- assume hydrocarbons and detergents	Low	
	Wash Bay Water	Unknown	Liquid	- unknown content / source	Low	

Category	Feedstock material	Organic / Inorganic	State	Odour factors	Odour Contribution Potential	Notes
	Waste Water	Unknown	Liquid	- unknown content / source - could contain organic waste / anaerobic	Medium	

* these are assumed to be inorganic chemicals but included within the ERA 53 definition of organic wastes

** Treated timber was previously a regulated waste and not considered an acceptable composting feedstock but has been found to be a composting feedstock in the past. As of February 2019 under the revised Regulated Waste Framework, treated timber is no longer a regulated waste leading to concerns it could find its way into composting facilities. Phase 2 of this project will assess its suitability from a contaminant perspective but for now it is considered a feedstock.

Section 4 – key findings and recommendations

- A long and varied list of known and potential composting feedstocks has been identified and by qualitatively assessing each feedstock against a number of key odour risk factors, it is possible to assess the odour contribution potential of each feedstock.
- This identifies those feedstocks which pose a higher risk of causing or contributing to odour issues in a composting process, and allows appropriate mitigation strategies to be targeted.
- A number of feedstocks are considered to have a high or very high potential odour contribution in a composting process. The materials considered to have very high potential odour contribution include:
  - Abattoir and animal processing waste
  - Animal Waste, including egg waste and milk waste
  - Hide curing effluent
  - Tallow Waste
  - Organics extracted from mixed household waste / MSW
  - Food processing effluent, solids and treatment sludges
  - Grease trap – both untreated and treated / dewatered grease trap sludge
  - Nightsoil, septic wastes and sewage sludge or treatment tank residues
  - Sewage treatment tank or treatment pit liquids, solids or sludges
  - Landfill leachate

Recommendations – Odour risk of feedstocks

- DES should consider whether there is a need for more stringent regulation or conditioning on sites that receive feedstocks considered to have a high or very high contribution to odour risk. That is not to suggest that these feedstocks are not suitable for composting, but that additional control measures may be warranted such as maximum blending ratios, additional requirements for their storage and mixing, more sophisticated processing, or additional analysis and documentation requirements.

5 UNDERSTANDING ODOUR, ITS MEASUREMENT AND ASSESSMENT

Odour can be defined as the sensation response that is generated from the interaction of volatile chemical species in air when inhaled through the nose, interacts with the olfactory system and registers in the brain. Common volatile species that give rise to unpleasant odours include sulfur compounds (e.g. sulfides, mercaptans), nitrogen compounds (e.g. ammonia, amines) and volatile organic compounds (e.g. esters, acids, aldehydes, ketones, alcohols) (Leonardos *et al*. 1969).

In general the terms odour, smell, aroma and scent tend to be used interchangeably, though often in a different context. The words 'aroma' and 'scent' can be used to describe both pleasant and unpleasant smells but are commonly used to describe pleasant odours like food, flowers or perfume. By contrast, the word 'odour' tends to present a negative perception and is used to describe unpleasant and annoying smells.

Environmental odours from anthropogenic origin are usually emitted from industrial and agricultural activities, including wastewater treatment plants (WWTP), food industry, rendering plants, landfills, livestock buildings, foundries, petrochemical parks, slaughterhouses, paper and pulp facilities, and composting activities. Air emissions containing odorous compounds released from such activities have the potential to interact with receptors, generally in a negative fashion. This impact has the potential to cause annoyance within a community, and if this annoyance persists over time, the emissions can become a nuisance and impact on the quality of life of community members. This often leads to complaints being registered with environmental authorities and the need to regulate odour pollution to resolve conflicts (Brancher *et al*. 2017).

5.1 Odour Dimensions

Odours can be characterised using five key dimensions:

- **C**oncentration
- **I**ntensity
- **C**haracter
- **O**ffensiveness, and
- **P**ersistency

The CICOP dimensions are the characteristics of odours that can be effectively measured by analytical (physicochemical analyses), sensorial (dynamic olfactometry) and sense instrumental methods (electronic nose). A combination of analytical and sensorial methods is the most widely used for the characterisation of odours (Gostelow et al., 2001: Capelli et al., 2008).

5.1.1 Concentration

Odour concentration is the most used dimension to characterise odours for regulatory purposes. The determination of odour concentration provides directly comparable data among odour sources. Odour concentration is also used to calculate odour emission rates and provide input data for atmospheric dispersion models (Bockreis and Steinberg, 2005, cited in Brancher *et al*. 2017).

Odour concentration is typically determined in a laboratory environment by dynamic dilution olfactometry using an olfactometer (Laor et al., 2014, cited in Brancher *et al*. 2017). There are no instrumental methods that predict the olfactory responses in humans to a satisfactory level, so the human nose is still used as the most suitable sensor (Ruijten et al., 2009, cited in Brancher *et al*. 2017). Human assessors are trained and calibrated to use the olfactometer (Brancher *et al*. 2017).

Determination of odour concentration is standardised in:

- Australia and New Zealand - AS/NZS 4323.3.2001 (AS/NZS, 2001)
- Europe - EN 13725:2003 (CEN, 2003)
- US - ASTM E679-04 (ASTM, 2011)
- Germany - VDI 3884 (VDI, 2015b)

In the Australia and New Zealand standard - AS/NZS 4323.3.2001 (AS/NZS, 2001), one odour unit (1 ou) is associated with a specific concentration of n-butanol, the certified reference material. The reference odour mass (ROM) is the accepted reference value for an odour unit. Accordingly, in AS/NZS, (2001), 1 ROM is equivalent to 123 µg n-butanol (CAS 71-36-3) evaporated in 1 m^3 of neutral gas (i.e. odourless air) at standard conditions.

This produces a concentration of 40 ppb (µmol/mol). This relationship is defined only at the odour perception threshold (OPT), also called Z_{50} or the detection threshold, which differs from the recognition threshold. Standard conditions for olfactometry are established at room temperature (293 K) and normal atmospheric pressure (101.3 kPa) on a wet basis and are derived from ISO 10780. This applies both to measurements of odour concentration and the volume flow rate of odour emissions. These conditions were chosen by convention to reproduce typical conditions for odour perception (Brancher *et al*. 2017).

Human sensitivity is at the core of odour evaluations (Brancher *et al*. 2017). AS/NZS, (2001) sets out the requirements for selecting and maintaining odour assessors (or panellists) used to measure odour concentration. The panel should reflect the average odour perception of a population considered ‘normal’. Only panellists with average olfactory sensitivity to n-butanol, i.e. those within the range of 20-80 ppb_v and a defined standard deviation, are selected for the evaluations.

A sample of odorous air can be described in terms of the volume to which it must be diluted for its intensity to be reduced to the level of its OPT. This means that the more dilution necessary to make an odour sample undetectable, the higher the odour concentration. The dilution factor necessary to achieve the OPT is known as the odour concentration, which is measured in odour units. The OPT of a complex mixture of odours or single chemical compound is the concentration at which 50% of the panel is able to detect the diluted sample of odorous air under laboratory conditions (CEN, 2003; AS/NZS, 2001). The key elements of the European standard are the quality criteria for accuracy and repeatability (Klarenbeek et al., 2014, cited in Brancher *et al*. 2017).

Odorous pollutants can be measured in terms of their chemical composition (i.e., mass concentration) by physicochemical methods, for example by gas chromatography coupled with mass spectrometry (GC-MS) or select ion flow tube mass spectrometry (SIFT-MS). However, these methods do not provide context around the nuisance impact on human receptors of odorous substances, which also depend on the character, perceived intensity or hedonic tone of the constituent compounds, the way these compounds interact in a mixture, as well as sensitivity and the subjective attitudes of exposed individuals (Brancher *et al*. 2017). Due to these limitations, different measurement approaches are necessary to quantify odours when compared to conventional air pollutants (Nicell, 2009, cited in Brancher *et al*. 2017).

5.1.2 Intensity

An odour’s concentration and intensity are not directly interchangeable terms. The intensity is defined as the strength of odour perception or the magnitude of the stimulus that causes the sense of smell. Odour intensity is quantified based on reference scales, where the perceived intensity of an odour is compared to the intensity of a standard chemical substance (n-butanol for olfactometry). The standard and reference scale commonly used in Australia for odour intensity measurement is from Germany (VDI 3882 – Part 1: 1992 (VDI, 1992).

The principle of the German standard is to present the odour sample to a panel at different degrees of dilution, from just below to well past the detection level, using a dynamic dilution olfactometer. Assessors are instructed to indicate a value for the perceived intensity in each exposure based on a seven-point scale. The scale is as follows:

0 – not detectable

1 – very weak

2 – weak

3 – moderate (distinct)

4 – strong

5 – very strong

6 – extremely strong

The concentration of an odour above its OPT and its perceived intensity are understood to be related as a logarithmic function, derived theoretically in accordance with the Weber-Fechner Law, or as a power function, represented by Steven's Law.

Weber Fechner Law:

$$I = a\log C + b$$

Stevens Law:

$$I = kC^n$$

where: I is the odour intensity; C is the odour concentration; and a, b, k and n are constants

This relationship is important in understanding the annoyance potential of odours, or when comparing different odours from an activity or neighbouring activities, as not all odours elicit the same response at an equivalent concentration. Taking this a step further, this relationship between odour concentration and intensity suggests that a single concentration-based criterion (e.g. an annoyance threshold of 5 ou) to effectively assess the nuisance impact of all odours is not practicable. An example of how the relationship between odour concentration above threshold and intensity can be presented and interpreted is presented in Figure 4 below.

The data shows that at an odour intensity rank of 'weak' (VDI rank = 2), the concentration could range from approximately 2 to 6 ou, depending on the source. By contrast, if the odour criteria were based on 2.5 ou, the perceived odour intensity would be between a little more than very weak and up to a little more than weak. Notwithstanding this, the question should be asked whether an intensity rank of 'weak' should be the annoyance threshold.

In Victoria and previously in Western Australia, EPA has based its ambient odour measurement performance criterion on a moderate (distinct) intensity level. Based on odour relationships for this facility, an odour criterion of moderate would suggest that a concentration of between 5 and 11 ou (depending on the stockpile age) would be more appropriate. This approach could be considered for different feedstocks and stockpile age at composting facilities in Queensland.

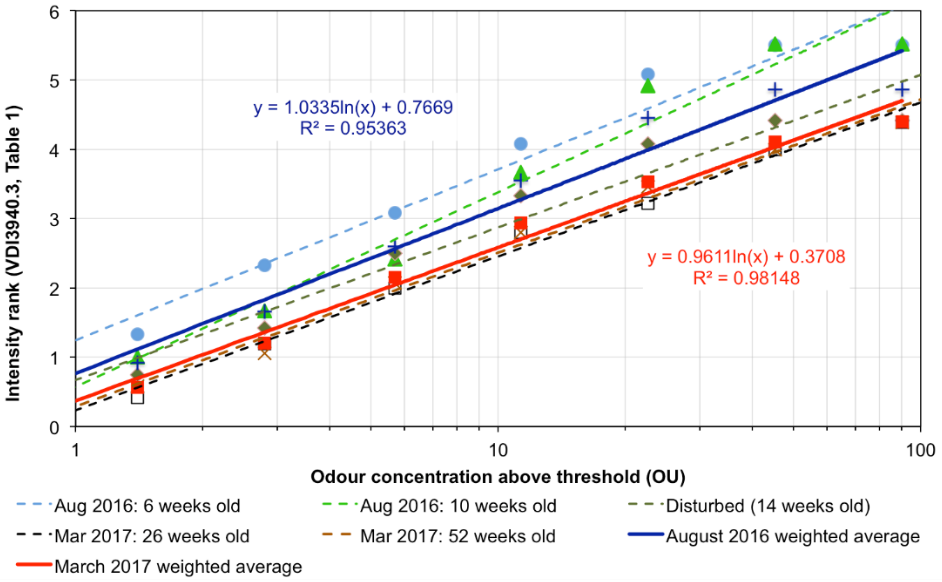

Figure 4: Example of odour concentration versus intensity relationship for green waste windrows of varying ages (Balch, 2017)

5.1.3 Character

The character of an odour is a nominal scale of measurement range in which the odour is characterised by using a reference vocabulary. An example of an odour wheel developed for compost odours prepared by Suffet *et al*. (2009) is presented in Figure 5. Odour wheels can also be used to support other methods of analyses, such as instrumental techniques (GC-MS) to better outline the nature of odour impact (Hayes, *et al*., 2014).

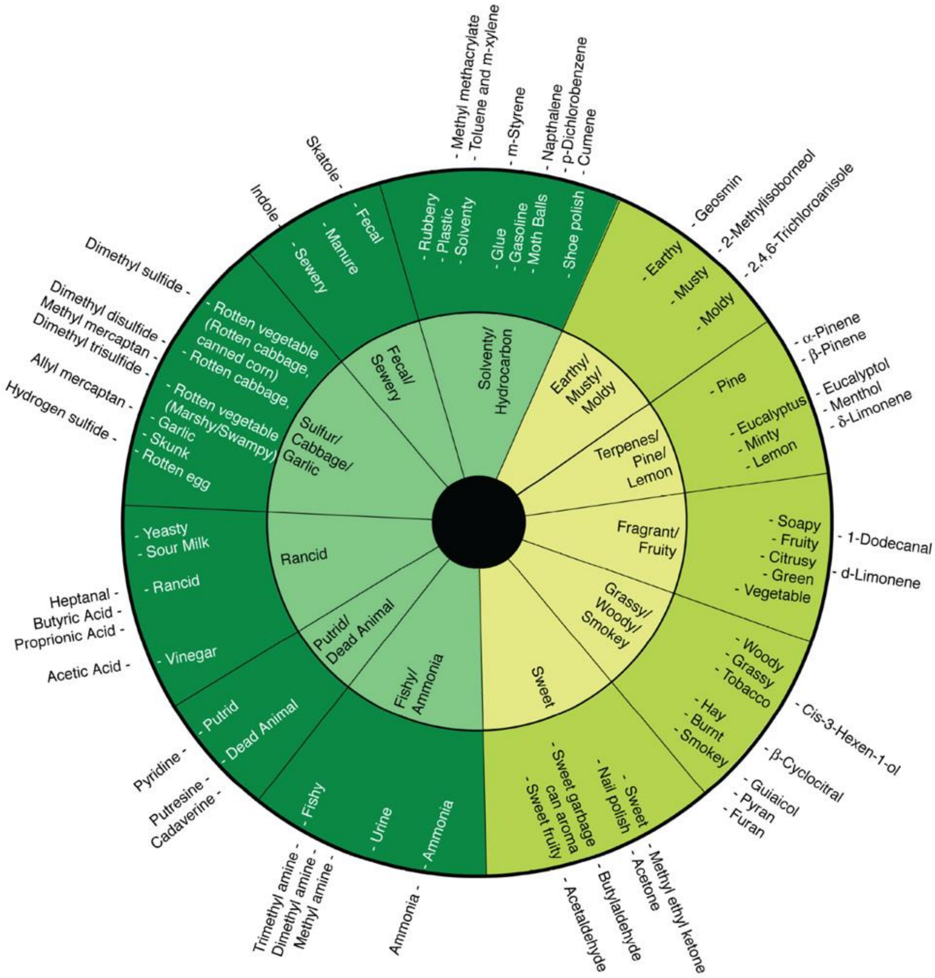

Figure 5: Compost Odour Character Wheel (Suffet et al, 2009)

5.1.4 Offensiveness (hedonic tone)

Offensiveness, or hedonic tone, is a measure of the pleasantness and conversely unpleasantness of an odour at a certain concentration/dilution. Like intensity, assigning a hedonic value to a sample is subjective to each assessor. Personal experiences, recent olfactory memories, events in childhood where certain odours are remembered with nostalgia or disgust can impact the evaluation (Brancher *et al*. 2017).

Though there is no widely recognised and accepted scale to assess odour offensiveness, the German standard (VDI 3882 – Part 2: 1994 (VDI, 1994) follows a suprathreshold dynamic dilution method to evaluate the hedonic tone of odorous air samples utilising a 9-point scale (from -4 (extremely unpleasant) to +4 (extremely pleasant) with 0 being neutral. Despite the intrinsic subjectivity involved in the determination of offensiveness, by using a standard approach, including a preselected panel with principles for participation, the results may be considered representative (Brancher *et al*. 2017).

5.1.5 Persistency

Persistency describes the rate at which an odour's perceived intensity decreases as the odour is diluted in the atmosphere downwind from the source (McGinley et al., 2000, cited in Brancher *et al*. 2017). The greater the volume of air necessary to dilute an odour below its OPT, the more persistent the odour is (Brancher *et al*. 2017).

5.2 Factors for assessing odour nuisance

The dimensions (or characteristics) of odour are evaluated to determine the annoyance potential of odour on an individual basis. Based on the differences, annoyance will occur for different odours in different combinations of their dimensions, i.e. differences in their perceived intensity, hedonic tone, character or persistence at different concentrations, not just at the same concentration.

When assessing the impact of odours on receptors, it is important to understand the technical difference between annoyance and nuisance. Van Harreveld (2001) suggested that, “annoyance is the adverse effect occurring from an immediate exposure. Nuisance is the adverse effect caused cumulatively, due to repeated events of annoyance typically over an extended period.”

Consequently, to evaluate odour nuisance, the dimensions of odour must be considered with the frequency of odour episodes, the duration of the odour episode and situation context (location) in which the odour is experienced.

The FIDOL factors - frequency, intensity, duration, offensiveness and location - influence the extent to which odours adversely affect communities and this information can be used as a basis for conducting odour impact assessment studies (Freedman and Cudmore, 2002; Nicell, 2009).

A summary of the definitions of the FIDOL factors is presented in Table 3.

Table 3: Definitions of the FIDOL factors

Factor	Description
Frequency	How often receptors are exposed to odours
Intensity	Perception of the odour strength or odour concentration
Duration	Elapsed time during a particular odour episode
Offensiveness	The subjective rating of the (un)pleasantness of an odour
Location	Sensitivity or tolerance of the receptor; related to the land use

It is generally accepted that the FIDOL factors provide a reasonable way of characterising odour impact. Regulatory guidance on odour impact assessment commonly maintains that the assessment of odour impact or nuisance is a complex issue that requires an understanding of the various characteristics and components of an odour (i.e. FIDOL) and its impact on the receiving environment.

Notwithstanding this common guidance, most current odour guidelines and statutory requirements provide for two distinctly different odour impact assessment approaches in planning and regulatory scenarios, neither of which considers all of the FIDOL factors nor do they assess odour impact in the same way (Balch *et al*., 2015).

Section 5 – key findings

- Odour concentration is the most commonly used odour dimension to characterise an odour for regulatory purposes and is measurable by well established olfactometry methods in a lab setting. However, other dimensions such as intensity, character, offensiveness and persistency are also important in assessing or describing a nuisance odour (together the CICOP dimensions of odour).
- The assessment of odour impact is complex. The FIDOL factors describe the key factors that influence the extent to which odours adversely affect communities – they include

Section 5 – key findings
frequency, intensity, duration, offensiveness and location. There is some overlap with the CICOP dimensions which describe a particular odour, but the FIDOL factors are more specific to a site and community and can be used to assess odour impact of an operation.

6 ODOUR IMPACT ASSESSMENT

6.1 Atmospheric dispersion modelling

6.1.1 Types of odour models

The transport and dispersion of pollutants are affected by different scales of atmospheric motion. Scales are classified according to their size as microscale, mesoscale, synoptic and planetary scale or macroscale (Godish, 2004). The planetary boundary layer (PBL) is the portion of the troposphere that is directly influenced by the Earth's surface and responds to the combined action of mechanical and thermal forcings (Stull, 1988).

Air quality not only depends on emission sources, but also, more decisively on meteorological parameters with multifaceted characteristics over various spatio-temporal scales. The transport of a pollutant emitted into the PBL responds to the action of mechanical turbulence (wind speed, presence of obstacles, topography) and/or thermal turbulence (heating and cooling of the Earth's surface) (Juneng et al. 2011).

The qualitative aspect of dispersion theory is to describe or predict the fate of atmospheric emissions from a source. Quantitatively, dispersion theory provides a means to estimate concentrations of a pollutant in the atmosphere at any given location using meteorological parameters, source characteristics and topographical features. The most frequent approaches applied to describe the turbulent diffusion and develop air pollution models are as follows (Zannetti, 1993; Seinfeld and Pandis, 2006; Colls and Tiwary, 2010):

- Langrangian - where variations in concentration are described in relation to the moving fluid.
- Eulerian – where the behaviour of the species is described in relation to a fixed coordinate system. The Eulerian description is a common form to describe heat and mass transfer phenomena.
- Gaussian – where Gaussian models are constructed based on the normal probability distribution of fluctuations in the wind vector (and therefore pollutant concentration). Strictly speaking, this approach is a subset of the Eulerian models. However, generally Gaussian models are treated separately.
- Semi-empirical – are mainly based on empirical parameterisation of atmospheric processes.
- Stochastic - where semi-empirical or statistical methods are used to analyse periodicities, trends and interrelationships of air quality measurements and to forecast episodes of air pollution.
- Receptor - considers the concentrations observed in a receptor point to estimate contributions of different emission sources.

Mathematical models are commonly used to predict concentrations in ambient air downwind of emission sources (Nicell, 2009). In general, Gaussian plume and Gaussian puff atmospheric dispersion models are most frequently used.

Gaussian plume models, such as AUSPLUME and AERMOD, adopt steady-state meteorological conditions applying throughout the entire modelling domain, which change on an hourly basis over the modelling year. Steady state plume models can therefore incorporate observed surface data from single meteorological stations. The AERMOD model is also able to incorporate upper air observations and prognostic upper air profile data. Given the assumption of steady state uniform meteorological conditions applying across the entire modelling domain, Gaussian plume models should not be used in regions of complex terrain and conditions where the assumption of uniform meteorological conditions would not apply. The model formulation also breaks down under calm conditions, meaning that they should also not be used when calm/light winds are frequent or are the controlling factor for poor dispersion of emissions from a source.

In contrast, Gaussian puff models such as CALMET, use spatially and temporally varying meteorological fields which track individual “puffs” over three-dimensional grid domains. They are therefore suitable for use in calm conditions. Puffs are tracked over successive hours meaning that each hour’s simulation may contain puffs that were emitted during previous hours, which have been advected throughout the modelling domain in response to spatially and temporally varying winds. Gaussian puff models therefore need to be supported by meteorological models, which produce hourly changing three-dimensional meteorological fields on the basis of observations from weather stations and/or prognostic or diagnostic meteorological model predictions.

Prognostic mesoscale meteorological models (e.g., TAPM[9], WRF[10]) are mathematical simulations of the state of the atmosphere in time and space. These models are initialised using six-hourly mesoscale meteorological analyses (generated by weather forecasting models from observations). They utilise databases containing detailed topographical and geophysical fields, allowing hourly model predictions to be made over a smaller region at a finer grid resolution by manually solving the equations governing atmospheric dynamics. Model predictions are made over a series of successively finer scale “nests”, with each nest being initialised with the results of the previous larger-scale nesting. The resultant fine-scale meteorological fields are focused on a small spatial region of interest but are consistent with the synoptic conditions. They explicitly account for localised effects generated by topographical and geophysical features such as sea and land breezes, terrain channelling, and thermotopographic winds (MfE, 2004).

Given their use of synoptic scale analyses, prognostic models can be used to provide initial input to Gaussian puff models in regions where there are no local meteorological observations available. Observed surface and upper air data can also be assimilated into model runs to enhance the model predictions.

Diagnostic meteorological models do not prognostically solve the equations of atmospheric dynamics, but rather interpolate a series of irregularly spaced meteorological observations or prognostic model predictions onto a regular three-dimensional grid. Small adjustments are then made to eliminate divergence and to ensure that predicted winds flow over or around topographical features rather than through them or into the ground. Prognostic model predictions are often downscaled or refined using a diagnostic wind field model.

CALMET is a diagnostic meteorological model that can be initialised by the 3D gridded output from the prognostic TAPM and WRF models (NO OBS mode), or observed surface and upper air sounding input data (OBS mode), or a combination of both (Hybrid mode) to simulate the meteorology at scales down to 100 m or lower, which in turn can be used in CALPUFF to simulate plume transport.

Another model used for odour dispersion in Europe is AUSTAL2000, which is a Lagrangian particle tracking air dispersion model that has implemented its own diagnostic wind field model. Rather than tracking pollutant puffs, particle models track millions of individual ‘particles’ as they are advected over the modelling domain. They are therefore computationally expensive and may take a long time for simulations to complete.

The model suite selected for assessments needs to be justified on a case by case basis. The most commonly used models in Australia for odour assessments are AUSPLUME, AERMOD and CALPUFF, with AUSPLUME being used less nowadays

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[9] TAPM – The Air Pollution Model (Hurley, 2008)
[10] WRF – Weather Research and Forecasting Model (WRF, 2019)

since EPA Victoria switched to AERMOD as their regulatory model in 2014. Notwithstanding that, many existing composting and waste management facilities in Queensland and Australia are likely to have been assessed as part of their original development approvals using the AUSPLUME model.

As composting facilities are typically characterised by many fugitive sources of odour (receival areas, open windrows, windrow turning, maturation pads, leachate dams, biofilters), and are often sited in areas of relatively complex terrain (e.g., those co-located with landfills in ex-quarry sites or in semi-rural areas and the outskirts of major cities and towns) where wind channelling, slope flows and calm or night time stagnant conditions may be an important feature, a dispersion model that can suitably address these complexities is recommended.

Other important considerations should include causality issues (i.e., the length of time taken for the pollutants to travel from point A to point B) and source to receptor distance (i.e., near-field or far-field impacts) and the associated uniformity of the meteorology.

When selecting a model for an odour impact assessment of a composting facility, certain questions should be asked:

- Is the terrain steep or complex?
- Is the regional meteorology spatially uniform in the area of assessment between the source and receptors or will topography and land surface features influence plume transport?
- Are calm or light winds a common and important feature?
- Are re-circulation issues important?
- Are highly stable or stagnant atmospheric stability conditions a common and important feature?
- Are the sensitive receptor locations considered to be in the near- or far-field?

Advanced non-steady state Gaussian puff models (such as CALPUFF) tend to address most of these issues more adequately than the steady state Gaussian plume models (AUSPLUME, AERMOD). In particular, CALPUFF accounts for a variety of effects such as the spatial variability of meteorological conditions, causality effects, dispersion over a variety of spatially varying land surfaces, terrain induced plume divergence, fumigation, and low wind-speed dispersion. CALPUFF has various algorithms for parameterising dispersion processes, including the use of turbulence-based dispersion coefficients derived from similarity theory or observations (MfE, 2004), while plume models such as AUSPLUME rely on dispersion coefficients like the Pasquill-Gifford classification scheme.

CALPUFF is generally run using 3D wind fields generated through the CALMET meteorological pre-processor, however, a more simplified single site wind field like that used to drive a plume model can be used where adequate detailed meteorology is not available. Use of CALPUFF overcomes some of the limitations of the Gaussian plume formulation, which neglects the effects of causality (producing a succession of “lighthouse beam” plumes extending to the edge of the modelling domain), treats individual hours independently from all other hours, and breaks down under calm and low wind speed conditions (MfE, 2004).

Plume and puff models can each be run using observed or prognostic (modelled) meteorological datasets. While the use of meteorological observations would appear, at face value, to be the optimal option for simulating plume transport, there are many considerations and issues with observed data sets that make its use difficult and less attractive for use. Instrument sensor quality, siting, data averaging interval, and unit of measurement for data logging are some of the important considerations.

In particular, sensor selection is very important for measuring wind speed and direction, with commonly used wind vane and cup anemometer sensors being relatively insensitive to light winds compared to more advanced sonic anemometers, resulting in poor data on calm and light wind conditions.

Siting is also very important as the wind and turbulence profile at the sensor location, for instance at the site of the odour emission source, may be quite different to that at the receptor and the area in between, and vice versa if the sensor is sited nearer to the receptor than the source. It is important that meteorological observations used with atmospheric dispersion models are representative of the region to be modelled rather than reflecting the microclimatic controls of the site such as individual trees or structures.

6.1.2 Short term averaging periods and peak-to-mean theory

On average a typical human inhalation occurs over a period of 1.6 seconds (Mainland and Sobel, 2006), meaning that humans may perceive odours over short term durations. In contrast atmospheric dispersion models generally calculate hourly predictions. Two approaches are typically adopted for odour impact assessment accounting for this difference in timescales:

- Calculate hourly mean concentrations, which may underestimate odour short-term concentration peaks and thus mask nuisances, and
- Calculate short-term odour concentrations from the 1-hour mean values (Drew, et al, 2007, cited in Brancher *et al*. 2017).

Dispersion model results therefore need to be adapted somehow to parameterise the short-term peak odour concentrations on the basis of hourly-mean predictions. It is assumed that the determination of the peak concentration is more appropriate to describe the odour sensation of the human nose than the longer-term mean value.

The utilisation of a constant factor to mimic the human nose is a simplification, since this number depends on the distance from the source, atmospheric turbulence (i.e., stability), intermittency, and source configuration.

Most dispersion models provide for the determination of ground-level concentrations over a range of averaging periods based on their hourly calculations. The shortest averaging period provided by AUSPLUME within the model's formulation is 3-minutes (details of this formulation are provided in (Victoria EPA, 1985, p. 40; and MfE, 2004), while CALPUFF only provides 1-hour averages.

The most common approach used for estimating peak sub-hourly average pollutant concentrations from hourly model predictions is the following power law function:

$$C_t = C_{60} \left[\frac{60}{t}\right]^x$$

Where:		
	C_{60}	= concentration for one-hour average,
	t	= averaging time, in minutes,
	C_t	= concentration for time of t minutes,
	x	= is a coefficient ranging from 0.17 to 0.6.

The exponent x in this power law function is used to adjust peak ground-level concentrations for different atmospheric stability conditions. A typical value of 0.2 is used for x, for general use across all stability classes. However, the exponent can range from less than 0.2 for tall stacks in highly convective conditions to as much as 0.6 for low-level point and fugitive releases in stable atmospheric conditions (MfE, 2004).

6.1.3 Odour emission rates for dispersion modelling

Odour emission rates are a critical input to the assessment of impacts from composting facilities using dispersion models. In Queensland, composting facilities tend to comprise open windrow methods, which present significant challenges in sampling and measuring air emissions.

In other Australian states and in many overseas developed nations such as in Europe, North America and parts of Asia, organic waste composting is conducted in closed vessel systems, in buildings or using mechanical aeration and ventilation systems where air can be captured and controlled, before being released through a stack (post-odour treatment) or open biofilter bed, making emissions sampling much easier. Notwithstanding that, odour and chemical emission studies of composting plants in Europe and Asia have used a variety of sampling methods including Flux Chambers, Witch's Hats and point source techniques.

Open windrows or stockpiles of composting material and leachate dams constitute area emission sources. In accordance with the Australian standard, AS4323.4 (2009), area source emissions should be sampled using a Flux Chamber device only, while the German odour sampling standard (VDI3880, 2011) does not describe the Flux Chamber, rather it provides for the use of a range of devices including the Witch's Hat, Wind Tunnel, and sampling by covering the area (if the source has a net outflow), e.g., biofilters. Gostellow et al. (2003) provided a detailed summary of odour measurement methods with a summary of advantages, disadvantages and potential applications of hood area source emission measurement techniques reproduced in Table 4 below.

There has been much debate in Australia and internationally on the comparison of odour emissions measured from Flux Chamber and Wind Tunnel devices and their application in odour impact assessment. The issues are yet to be settled, though there may be a case for both techniques in certain circumstances.

Key differences between the two dynamic hood methods is the rate of neutral ventilation air introduced to the enclosure, with the Wind Tunnel operated at a significantly higher flow rate than the Flux Chamber, the pressure differential, temperature and humidity in the Flux Chamber headspace, and the duration of time required to collect the samples. The Wind Tunnel is generally considered to be a more suitable device for sampling sources with a net air outflow, unless the rate of air from the source into the Flux Chamber is taken into account, along with the ventilation air due to the very low flow rate used in the Flux Chamber.

Table 4 Advantages, disadvantages and potential applications of hood area source emission rate measurement methods (Gostelow et al, 2003)

Technique	Advantages	Disadvantages	Applications
All	Isolates portion of emission surface, so can be used on complex sites with upwind interference; Higher concentrations measured – potentially more sensitive.	Many measurements required for heterogeneous sources; Potential to interfere with emission mechanisms; Can be difficult to relate conditions in the hood to field conditions; Suited to static surfaces only;	Complex sites with upwind interferences; Detailed surveys of different emission sources on a site.

Technique	Advantages	Disadvantages	Applications
		Can be difficult to form effective seal on some surfaces.	
Static flux chambers	Little dilution of emissions – good for low emission rates; Low equipment requirements; Rapid measurements.	Diffusive emissions can be suppressed through high chamber concentrations; Poor representation of boundary layer; Poor mixing in the chamber; Not suited to emissions from liquid surfaces.	Potentially useful for rapid measurements at many locations; Emissions from heterogeneous sites where spatial variability is being studied; Emissions from sheltered solid surfaces where wind effects are negligible.
Dynamic flux chambers	Potentially greater control over measured concentrations by varying sweep air flows.	Convective emissions can be misrepresented due to pressure effects; Diffusive emissions can be suppressed through poor representation of boundary layer; Can be slow to stabilise; Greater equipment requirements; Not suited to emissions from liquid surfaces.	Emissions from relatively homogeneous sheltered solid surfaces where wind effects are negligible.
Wind tunnels	Greater control over variables influencing emissions; More accurate representation of wind effects; Potential to develop wind/ emission rate relationships for dispersion model input.	Large equipment requirements; Difficulties in selecting/measuring representative wind speeds; Care required in design, particularly in terms of velocity and concentration profiles and pressure effects.	Emissions from relatively homogeneous solid or liquid surfaces where wind effects are significant.

In basic terms, a standard non-mechanically aerated compost stockpile can be considered to be a passive emission source. However, during the active phase in particular, the heat generated during thermophilic composting, when temperatures within the pile can increase to 60-70 °C and above, can develop a convective flow of air within and out of the windrow. In sampling open windrows at a green waste composting facility in Victoria, Pollock and Braun (2009) determined that measurements by Flux Chamber sampling, according to the AS4323.4 methods, during the first week of composting when outgassing is at its peak, underestimated specific odour emission rates (SOER, ou.m^3/m^2/s). This was determined when dispersion model predictions based on these SOERs were compared to complaint data. Subsequent modelling and assessment using measurements sampled with a Witch's Hat device along the windrow crest were in better agreement with the complaint data. The difference between the SOERs using the Witch's Hat and Flux Chamber devices was 20:1.

Pollock and Braun (2009) and Pollock *et al*. (2015) followed up this work by comparing SOERs from compost stockpiles sampled with devices of their own design, a Draped Wind Tunnel and Full Stockpile Enclosure (or temporary Green House), as illustrated in Figure 6. The ratio of the Full Stockpile Enclosure method to Flux Chamber was approximately 13:1, though this was in part due to an excessively high air velocity across the stockpile surface beneath the Full Enclosure due to a lack of fan control, that was likely to generate wind stripping.

Pollock and Braun (2009) and Pollock *et al* (2015) concluded that the Flux Chamber should not be used to measure odour emissions from active phase compost windrows and that facilities that have done so in the past are likely to have underestimated their odour emissions and impacts. They determined that the Draped Wind Tunnel was a more appropriate method for sampling stockpiles to account for the effect of emissions over the full cross-sectional perimeter of the pile and that while the Full Enclosure method was good, it was too costly and difficult and deploy on a routine basis. Given the unorthodox and cumbersome nature of the Draped Wind Tunnel, the use of a standard portable Wind Tunnel may be more appropriate if a representative number of samples are collected from across the crest and sides of the stockpile.

Figure 6: Sampling compost stockpiles using versions of the Draped Wind Tunnel (upper and lower left) and a Full Enclosure 'Greenhouse' method (upper and lower right) (Pollock and Braun, 2009 and Pollock et al, 2015)

Air Environment has also conducted similar experiments as part of an impact assessment on open windrows in the Australian Capital Territory (Balch, 2017) for a green waste composting site with 1,000 m separation distance. The assessment aimed to determine the potential for a buffer reduction to accommodate future residential development nearby. Odour sampling was conducted during very warm March (early autumn) and cool August (late winter) conditions. Measurements on stockpiles of varying maturity were taken using a Flux Chamber and a Wind Tunnel device during both surveys. Field ambient odour surveys were also conducted downwind of the facility during both surveys. Dispersion modelling was conducted using emission inventories developed from the two sampling methods in both seasons.

The study determined that dispersion model predictions based on Wind Tunnel measurements were in better agreement with field odour survey observations. Notwithstanding the difference in the stockpile surface area ratio at the facility between early autumn/late winter of 1.3, the total facility odour emission rates (OER) for the Flux Chamber and Wind Tunnel in March and August were 15,096 and 3,007 ou.m^3/s compared to the Wind Tunnel OERs of 108,285 and 26,157 respectively, i.e., Flux Chamber/Wind Tunnel ratios of total facility OERs of 0.14 and 0.12 (note: stockpile crest emissions were calculated from Wind Tunnel measurements and stockpile side emissions were calculated using Flux Chamber measurements and then combined).

Furthermore, this assessment suggested that the existing 1,000 m buffer was marginally adequate for the site. Not surprisingly, the assessment based on Flux Chamber measurements suggested that a reduction of the buffer by several hundred metres may be possible. A recommendation was made that the development should not go ahead.

An alternative approach developed in Belgium and adopted by the European Union in the EN16841.2 (2016) standard is to conduct field ambient odour assessments using an odour patrol while collecting site representative meteorological data suitable for use in a dispersion model. The approach requires the odour patrol to assess the horizontal dimensions of the odour plume at ground-level to determine ‘sniffing units per cubic metre’, which are similar to odour units but measured in the field rather than in the laboratory.

Based on the plume dimensions and corresponding meteorology, a dispersion model is run for the hours of the measurements and the odour emission rate of the source or entire facility are back-calculated from the model scenario in which the concentration contour isopleths match the odour patrol’s assessment of the plume’s size, shape and relative intensity. Once the facility’s OER is determined, the model can be run for the full year or more. This approach assumes that the facility’s OER is unchanging throughout the course of the modelling period.

Odour emissions measurement, and in particular the method used, is a critical part of the dispersion modelling and impact assessment process from organic waste composting facilities. The method used to measure emission rates can have a significant effect on the calculation of odour emission inventories and on impact prediction. In addition to the sampling method, the season and conditions under which measurements are conducted are also critical, with significantly higher emissions observed during the warmer seasons.

Other important factors to consider when measuring odour emissions from composting facilities is stockpile age and feedstock material. Stockpile odour emissions can vary significantly across the full life cycle from the formation of fresh waste material after shredding and blending to its complete maturation and the sale of the final product.

Over the life of a stockpile, odour emissions typically start out relatively high, depending on the type and freshness of the feedstocks, and can increase further as the thermophilic stage progresses, though the composition of odorous compounds and their concentrations can change during this process. Once this stage has concluded and the stockpile enters the curing stage with the core temperature decreasing below about 45 °C, odour emissions begin to decrease until they reach an earthy character of background concentration levels.

Aeration and temperature of windrows are also an important consideration in measuring odour emissions and developing odour emission inventories for use in dispersion models. Windrows managed with aerobic conditions tend to have lower odour emissions, however excessive mechanical (or forced) aeration of windrows can lead to odour stripping and elevated odour emissions.

Increasing the rate of aeration decreases the temperature and the temperature related odour generation effect but increases the odour emissions due to odour stripping. The decreased temperature from excessive aeration also slows the composting process. It is therefore useful to understand these conditions to account for them when odour sampling and developing an emissions inventory.

Measuring odour emissions from windrow turning is inherently difficult. Pollock *et al* (2015) determined that the operation of turning using a rotating drum turner raised the windrow OER by 70:1, while an excavator operating significantly slower than the turning machine increased windrow emissions by 7:1.

In a study conducted by Air Environment, a stockpile of green waste and another with a 50/50 blend of green and food waste returned OERs during turning using a windrow turning machine of 36,000 and 50,000 ou.m^3/s respectively.

This may be more odour than released by an entire facility under quiescent windrow conditions. How quickly a freshly turned windrow returns to a baseline OER after turning is another important factor. Pollock *et al* (2015) determined that OERs were still as much as three times the quiescent baseline level up to an hour after turning. Air Environment has found that emissions typically return to baseline levels within one to two hours of turning.

6.1.4 Geophysical features

Geophysical features refer to the topography and land surface characteristics in the area of the composting facility and surrounding region where sensitive receptors are affected.

Local topography can have several influences on plume transport and diffusion. Upwind terrain can alter the wind flow and turbulence characteristics from those measured at the nearest meteorological station. Hills or rough terrain can change wind speeds, directions and turbulence characteristics, and nearby water bodies can considerably dampen turbulence levels. Significant valleys can restrict horizontal movement and dispersion and encourage the development and persistence of drainage flows. Night-time values of horizontal turbulence can be considerably reduced. Sloping terrain may help to provide katabatic or anabatic flows (i.e. drainage of air down or up hillsides in response to changing vertical temperature profiles). (Katestone Scientific, 1998, cited in MfE, 2004)

It is important to account for land surface features, as these may affect plume transport. Atmospheric dispersion models therefore require land use classes to be specified within the modelling domain. Typical land use classes include:

- bare soil,
- sand,
- grass,
- sparse low to tall dense native vegetation including scrubland and forests,
- cropping lands,
- orchards,
- plantations,

- urban residential and commercial development,
- industrial complexes,
- cities, and
- water bodies.

The key physical elements of these land use classes addressed in meteorological and dispersion models are albedo (surface reflectivity of solar radiation), Bowen ratio (relationship of sensible and latent heat), leaf area index, soil (surface) heat flux, anthropogenic heat flux, and surface roughness length. Each of these parameters influences the energy flux and the flow of wind at the surface. This in turn effects plume dispersion and ground-level pollutant concentrations.

Topography and land surface features should be appropriately characterised in the model at a suitable grid resolution. There is no benefit in configuring a model to cover an area with a radius of 50 km around a facility at 1 km grid receptor and geophysical setup resolution if the nearest receptors are within 500 m to 2 km of the source.

Similarly, a model setup with 10 m grid resolution covering an extent of only 1 km from the source may be excessive without the detailed input data to drive the model, and also leaving important receptors outside of the modelling domain. A balance is required to address the important details in the model domain (terrain and land surface resolution), important receptors, model output file size and model run time.

6.1.5 Meteorology

There are two processes acting on a plume during its dispersion. The first is advection, which is the lateral transport of the plume by the wind. This is the dominant process; however, the process of diffusion is also important, especially under light or calm wind conditions. The two processes can be illustrated using the concept of a “puff” within a Gaussian puff dispersion model. The wind is the dominant mechanism acting to advect the puff from one location to another. As the wind speed increases the puff is diluted, effectively stretching the plume. As each puff is blown downwind, it also expands due to diffusion processes, decreasing in concentration.

Wind speed is therefore the most important meteorological parameter affecting odour concentration, with wind direction determining the location of the plume. The most important meteorological parameters governing diffusion are atmospheric stability/turbulence, which can be characterised using many different methods, and mixing height.

Composting windrows are ground level sources. The stereotypical conditions conducive to poor dispersion of emissions from such sources are light stable wind conditions, particularly during the evening and early morning when odour emissions can become entrained within slowly flowing drainage flows, travelling with little dilution along the path from source to receptor.

This is an important mechanism, but in Queensland other meteorological conditions may be more important for dispersion of odour from composting windrows. Under moderate wind speeds, the winds act to strip or draw out odours from the windrow surface. This effect can be significant, resulting in a well-defined and concentrated odour plume, which may be transported considerable distances downwind. Air Environment has previously detected odour from green waste composting under constant moderate wind conditions at downwind distances of over a kilometre from a composting facility.

Meteorological data collected onsite or close to a composting facility can be extremely useful when responding to complaints or managing environmental incidents. If a year of observations has been obtained, then the data may be suitable for use within an atmospheric dispersion model of the facility or included within annual reports to the environmental regulator. Alternatively, onsite meteorological measurements can be used to evaluate the suitability of modelled meteorological fields. Meteorological observations can be carefully analysed to help a composting facility understand the dispersion mechanisms governing their odour plume. This can provide useful odour mitigation insights.

A weather station has to be carefully sited, typically 10 metres above the ground, following the appropriate Australian standard. This ensures that collected observations are representative of the broader region rather than of the specific microclimatic controls on the composting site.

The following range of meteorological parameters is recommended for use in air/odour pollution circumstances, particularly if the observations are going to be used to develop a dispersion model meteorological file:

- Wind speed
- Wind direction
- Air temperature
- Temperature difference between 2 m and 10 m (used to calculate atmospheric stability at night)
- Solar radiation (used to calculate atmospheric stability during the day)
- Relative humidity.

Consideration should be given to installing a sonic anemometer rather than a cup and vane, as these have no moving parts and can accurately measure the low wind speeds required for dispersion models. It is also useful to install a datalogger with an internal modem, allowing direct access to observations. This allows the data from the station to be remotely viewed in real time; it provides easy and quick data access; and can be used to provide alerts triggered by important meteorological phenomena.

6.2 Field ambient odour assessment methods

Ambient odour assessments by field inspection methods have been documented in Germany (according to the VDI3940 standards) and Europe (according to the EN16841 standards) and are used extensively throughout Europe and Australia. In North America, field odour inspections have tended to use field olfactometry techniques based on Scentometer, Nasal Ranger and Scentroid SM100 technologies.

In Australia, Nasal Ranger and Scentroid SM100 based field olfactometry has been used for many years, however field assessments using various truncated versions of the VDI3940 odour intensity ‘sniff test’ evaluation method has been more common. Consequently, some environmental regulators have incorporated odour intensity into their guidelines and impact assessment criteria rather than dilution-to-threshold (D/T) units, which have been used in North America, based traditionally on assessments made with the Nasal Ranger device.

6.2.1 Field odour intensity surveys

Odour surveys conducted around industrial activities in Australia typically measure odour in terms of its intensity rank according to the VDI3882.1 scale. In Victoria, this seven-point scale has been simplified by EPA to a three-point scale (0 = not detectable, 1 = weak, and 3 = strong). The relationship between the two scales is presented in Table 5. Whichever scale is used, the common criterion for assessing potential annoyance is moderate (distinct) odour.

Table 5: Comparison of intensity reference scales

VDI 3940 intensity scale (based on VDI3882.1)		EPA Victoria intensity scale	
Rank	**Description**	**Rank**	**Description**
0	Not detectable	0	Not detectable
1	Very weak	1	Weak. Not potentially annoying
2	Weak		
3	Distinct (moderate)	2	Strong. Potentially annoying
4	Strong		
5	Very strong		
6	Extremely strong		

The VDI3940 method prescribes the use of 10-minute odour evaluations at each measurement location where 60 odour intensity observations are recorded at 10-second intervals. Measurements are made multiple times over a grid during a year-long survey. The method is also prescribed in the EN16841.1 Grid Method standard.

The VDI3940 method is based on the concept of the 'odour hour' in Germany, where odour nuisance assessment is based on a 90th percentile statistic and the odour hour is defined by odour being detected for at least 10% of an hour at a given location. The odour hour concept has not been adopted in Australia. As an alternative approach, the EN16841.2 Plume Method standard allows for a faster, more efficient measurement method that facilitates many more measurements to be made at more locations during a survey.

Instantaneous measurements are made within one to two minutes at each location with the objective of tracking the odour plume's spatial extent. As the VDI3940 approach takes 10 minutes or more to complete a measurement, far fewer sampling locations can be assessed in a survey and more assessors are required. The EN16841.2 method allows faster tracking of the plume to assess its dimensions within a short period of time, typically between one and three hours. This provides a snapshot of the plume's ground level footprint and its annoyance potential based on intensity values. Both approaches have been used extensively in Australia.

During the field odour inspections, a range of data is typically recorded. This includes, but may not be limited to:

- Project name, site location, activity description and operating conditions,
- Survey ID,
- Sunrise and sunset times,
- Magnetic declination for the site,
- Assessor name,
- Location by GPS coordinates, i.e. Map Grid of Australia (MGA) eastings and northings,
- Distance from pre-defined odour sources,
- Date and time of sample measurement,
- Minimum, mean and/or maximum wind speed measured with a hand-held anemometer,
- Wind direction measured with a compass, adjusted to True north,
- Air temperature,

- Relative humidity,
- Precipitation rate (subjectively assessed),
- Station pressure,
- Cloud cover (in oktas),
- General weather description,
- Whether or not any odour was detected. Where odour was detected, multiple records could be made for multiple odours described as the primary, secondary or tertiary odour in terms of the ranking of dominant or persistent odours. As such, the following information is collected as appropriate:
  - Odour intensity rank (VDI3882.1 scale),
  - Odour character or source of odour,
  - Duration of odour presence descriptor, e.g.
    - Not present,
    - Fleeting,
    - Intermittent/occasional,
    - Mostly present,
    - Continuous,
  - Hedonic tone (VDI3882.2 scale), and
  - Other comments.

Meteorological parameters should be recorded at each measurement location. The critical parameters at each location include wind speed and direction. Other parameters can also be recorded at the start and end of the survey and as conditions change during a survey, e.g., a cold change comes through, temperature or wind drops as the sun sets, or it starts raining.

Meteorology can also be measured from a permanent, stationary automatic weather station (sited to Australian standard requirements) to provide an assessment of the conditions in the general area. However, it is critical to record the wind conditions at ground level (approximately 2 m above ground) to capture the conditions at the time and location of the assessment.

Measurement data collected from field odour intensity surveys can be analysed in various ways to assess odour impact and annoyance potential. Figure 7 and Figure 8 illustrate the odour intensity rank, wind speed and direction during surveys around an abattoir and green waste composting facility respectively. Measurements were collected using the EN16841.2 approach where odour intensity is evaluated as the peak intensity experienced during a one-minute measurement, rather than every 10 seconds over 10 minutes. This way the plume extent over a one to three-hour period can be assessed. Figure 9 shows the data from field olfactometry measurements downwind of the same green waste composting facility. Conducting a series of field odour surveys with these methods during different conditions (e.g. plant operations, wind, temperature, atmospheric stability, time of day and season) and analysing the data in this way can provide a comprehensive assessment of nuisance potential and extent.

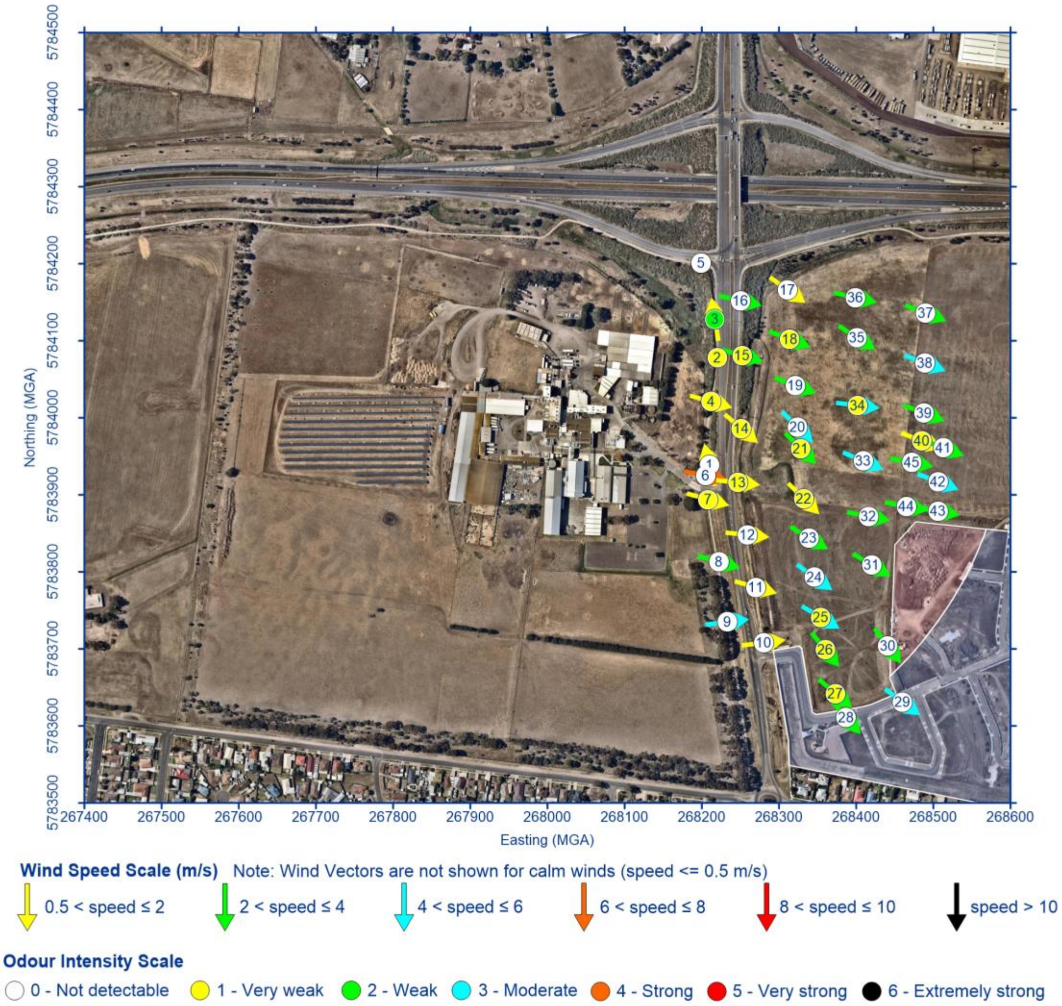

Figure 7 Field odour intensity survey results around an abattoir

Figure 8 Field odour intensity survey results around a green waste composting facility

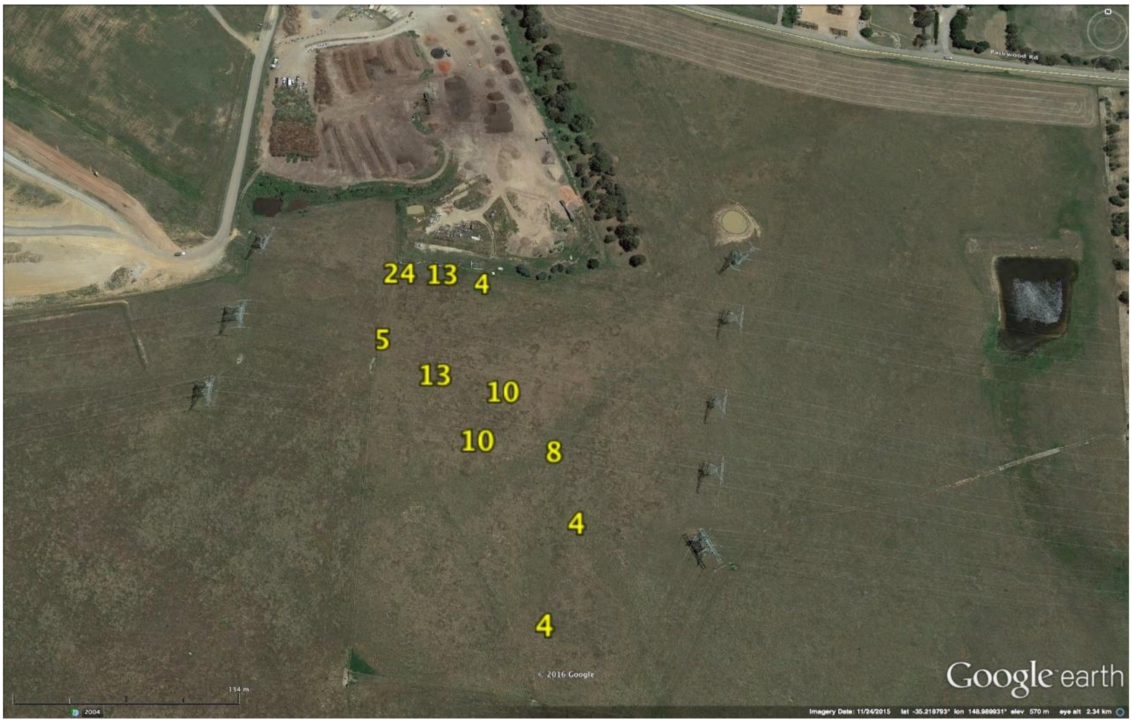

Figure 9 Field odour concentration survey results around a green waste composting facility using a Scentroid SM100 Field Olfactometer

The assessment techniques provide for frequency of odour episodes and their intensity to be evaluated across the entire region or at individual locations or zones. A zone may be a group of measurement locations such as a street or a group of receptors.

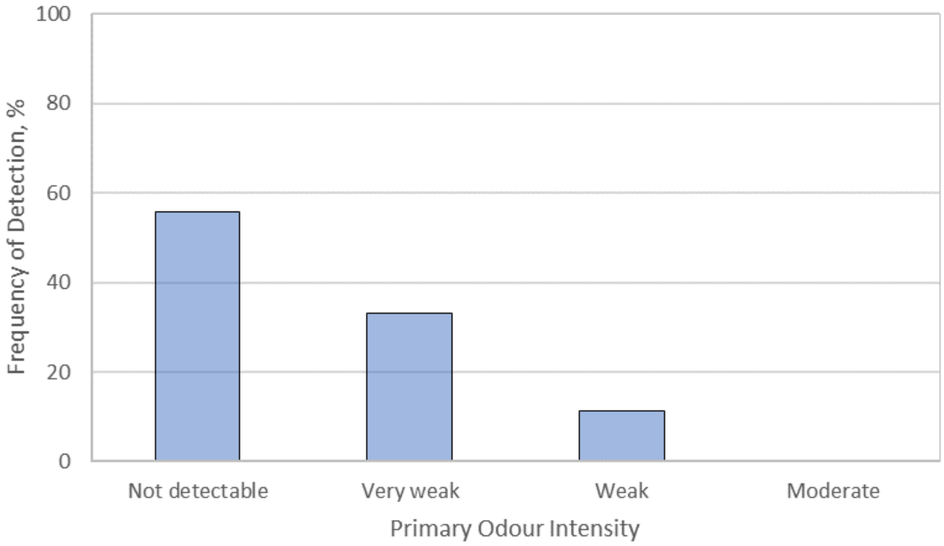

Figure 10 Frequency distribution of all odour sources (assessed as the primary odour) detected across the assessment area (Balch et al, 2015)

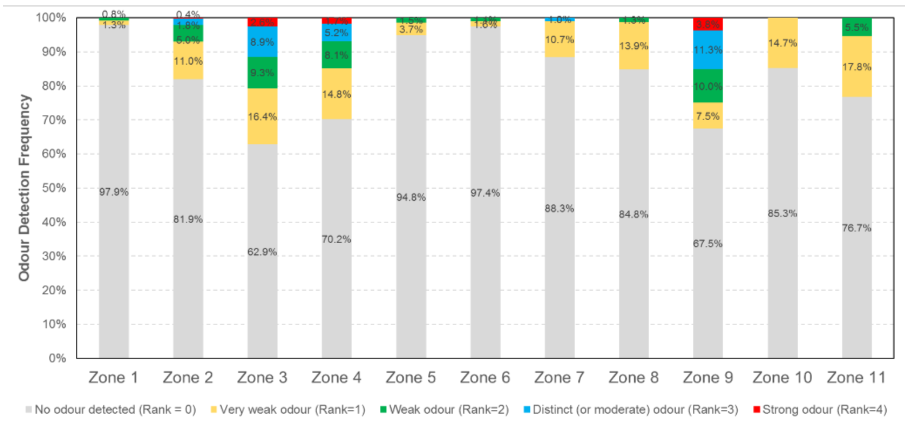

Figure 11 Frequency distribution of all odour sources detected across the assessment area by zone (Balch et al, 2015)

The frequency of odour episodes may be assessed according to the specific odour source, as shown in Figure 12.

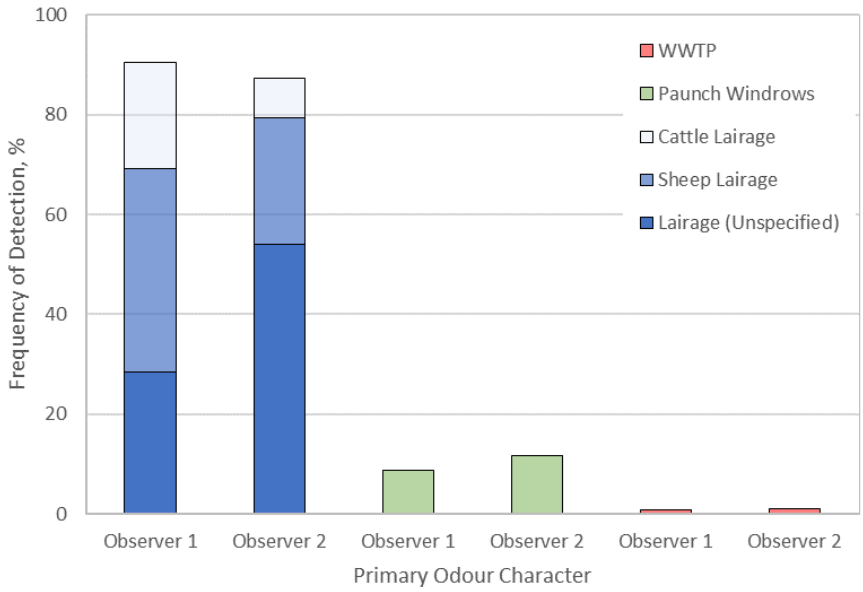

Figure 12 Frequency of observed odour according to its identified source

The duration in which an odour is present is also an important FIDOL characteristic that causes occasional annoyance from odours to become a nuisance if they persist. By recording information on the duration of time the odour was present in each location, analysis of the persistence of the odour can be made, as illustrated in Figure 13.

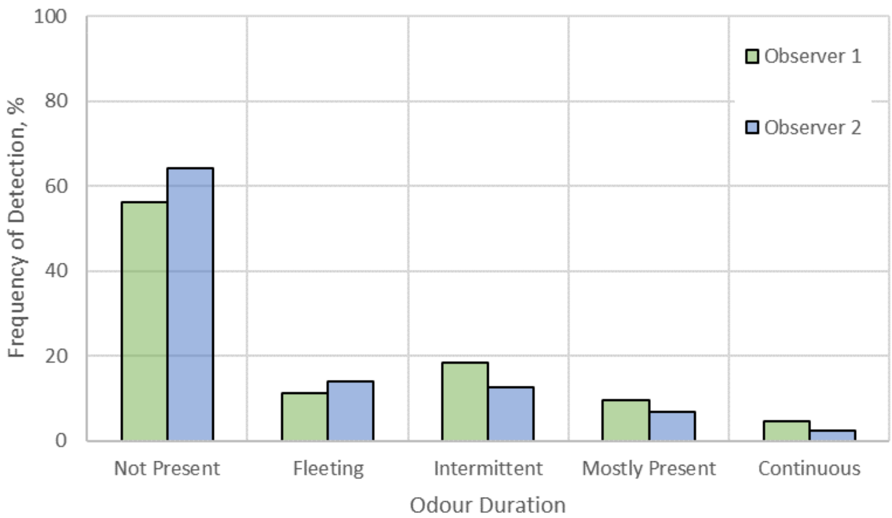

Figure 13 Frequency distribution of the duration of each odour episode

Hedonic tone can also be an important factor in assessing odour nuisance potential. A frequency analysis of hedonic tone is presented in Figure 14.

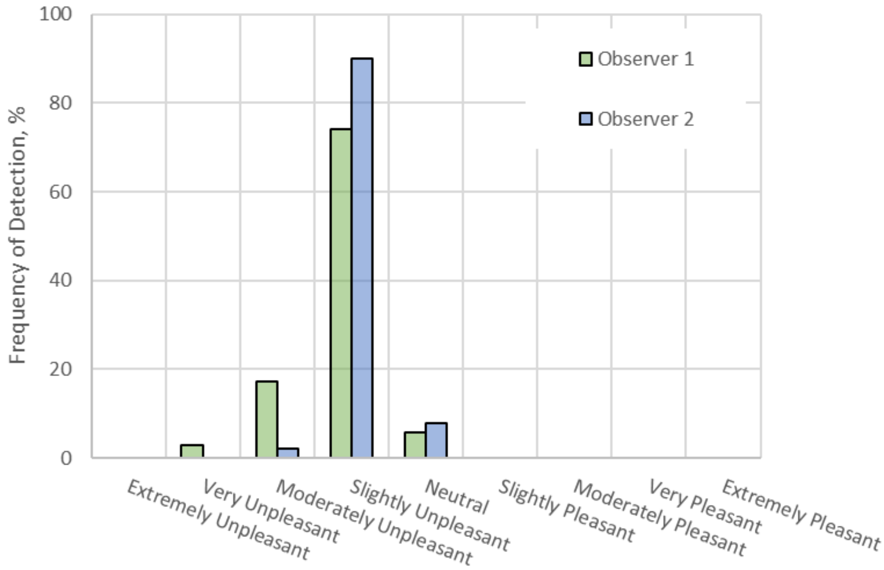

Figure 14 Frequency distribution of the hedonic tone observed for each positive odour episode

When interpreting odour impact, a critical factor in odour dispersion is the wind. While wind direction is important for identifying the location of the impact and for understanding geophysical influences on plume transport, it is often more useful to remove the wind's directionality from the analysis and assess the odour impact potential based on wind speed in any direction.

This is known as an analysis of the distance decay in an odour's intensity. This will assist the analysis if the wind tends to blow in a direction other than toward the main area of complaints or the area under assessment (e.g. in reverse amenity situations) and allows for surveys to be conducted and analysed whether the main receptor zones are being impacted or not.

The range of downwind distances for each observed odour intensity ranking is plotted in Figure 15.

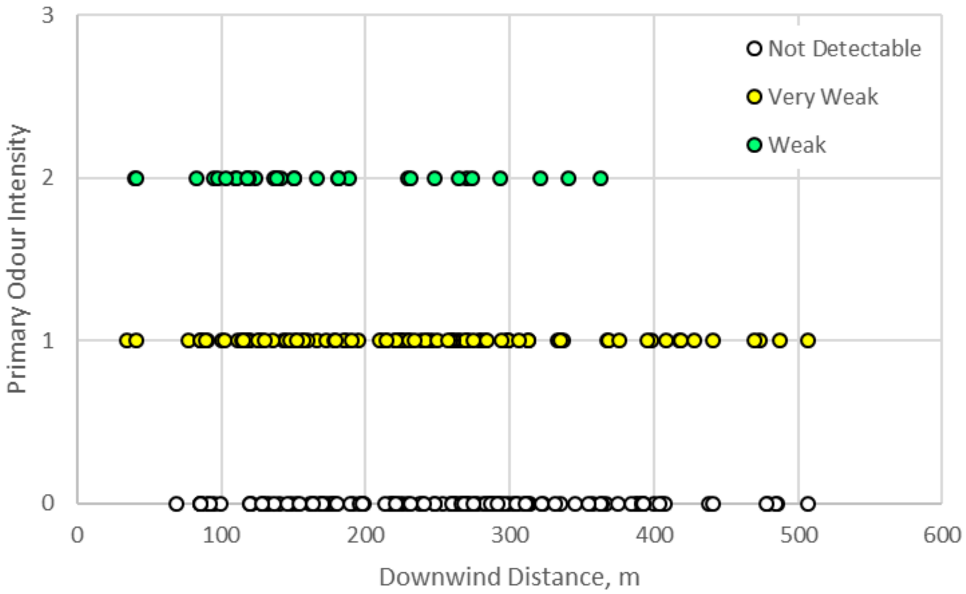

Figure 15 Downwind distances for each observed odour intensity measurement

It is then possible to assess the ranges in downwind distance in which different odour sources may be detected, as shown in Figure 16.

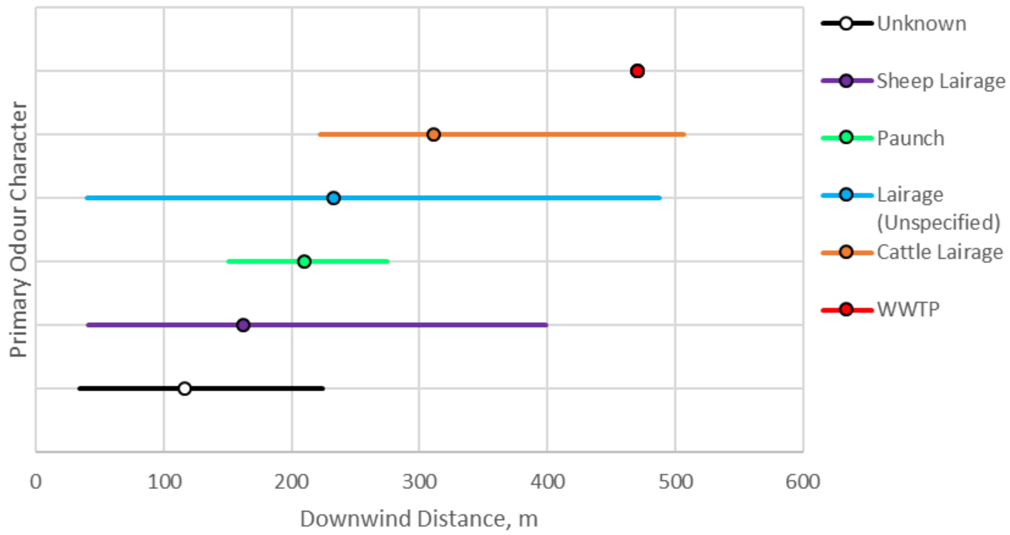

Figure 16 Downwind distance that each odour source was detected

Finally, an analysis can be conducted of odour intensity observed for all sources as a function of wind speed and downwind distance, as presented in Figure 17. This provides for an assessment of odour annoyance potential under varying wind conditions no matter the direction. This analysis is simpler in areas where local topography does not significantly affect plume transport.

An interesting conclusion drawn from the analysis in Figure 17 is that the mean distance from the source in which odour is detected increases as the wind speed increases. This seems counterintuitive to the general principle that increased wind speed increases odour dispersion and thereby reduces the ambient odour concentration. However, we have observed this effect on many occasions when conducting field ambient odour assessments around fugitive area sources such as composting facilities, sewage treatment plants, naturally ventilated broiler farms and abattoir/rendering plants and may be in part due to wind stripping.

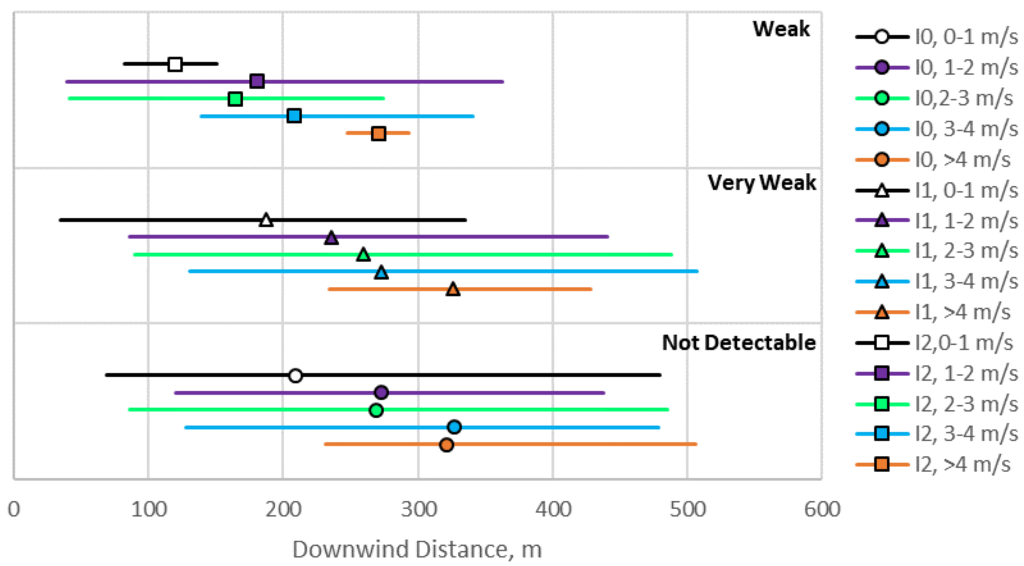

Figure 17 Perceived odour intensity by downwind distance and wind speed

Section 6 – key findings and recommendations

- Composting facilities are typically characterised by multiple point and fugitive sources of odour (receival areas, open windrows, turning activities, maturation pads, leachate dams, biofilters), and are often sited in areas of relatively complex terrain (e.g., co-located with landfills in ex-quarry sites or in semi-rural areas and the outskirts of major cities and towns) where wind channelling, slope flows and calm or night time stagnant conditions may be important features.
- Odour dispersion modelling can be an effective tool to assess odour impact on receptors, taking into account these complex factors, provided the right type of model is used. Models can also help operators and regulators to understand the effects of different variables such as weather conditions.
- Odour emissions measurements are a critical part of odour dispersion modelling and impact assessment to maximise their accuracy
- Typically, poor dispersion of odour emissions from composting facilities occurs during light stable wind conditions, particularly during the evening and early morning when odour emissions can become entrained within slowly flowing air flows, travelling with little dilution along the path from source to receptor.
- On the other hand, moderate wind speeds may strip or draw out odorous compounds from a windrow resulting in a significant, well-defined and concentrated odour plume, which may be transported considerable distances downwind.
- Meteorological data collected onsite at a composting facility can be extremely useful when responding to complaints, planning site operations to minimise odour impact or for use within an atmospheric dispersion model. Meteorological observations can be carefully analysed to help an operator understand the dispersion mechanisms governing their odour plume, which can provide useful odour mitigation insights. Weather stations have to be carefully sited, typically 10 metres above the ground, following the appropriate Australian Standard.
- Field odour surveys can be a useful tool to quantify and delineate an odour plume but they require careful planning and analysis of the data to provide a comprehensive assessment of nuisance potential and extent.

Recommendations – Odour Impact Assessment

- Odour dispersion models should be used to assess the impact of proposed new composting facilities and any existing facilities which have been subject to repeated odour complaints.
- Composting facilities should have a weather station on site to collected site-specific meteorological data to aid in responding to complaints, planning site operations to minimise odour impact and verifying odour dispersion modelling.
- Where an odour plume is known to exist, field odour surveys by appropriately trained people can be a useful tool to quantify and delineate an odour plume.
- A site specific odour management plan can bring together all of the above factors, identifying odour sources on site and supporting proactive measures to reduce the potential for odour generation.

7 IDENTIFYING AND QUANTIFYING ODOURS FROM COMPOSTING

7.1 Overview of chemical compounds in odours from composting

Many of the odorous chemicals associated with composting are described by the broad term, volatile organic compounds (VOCs). VOCs are organic molecules that have a high vapor pressure at room temperature. Common VOCs include the mercaptans, organic sulfides, amines, indoles, volatile fatty acids (VFAs), terpenes, alcohols, ketones and aldehydes (Haug 1993; Miller 1993; Epstein 1997).

The term volatile organic sulfur compound (VOSC) describes a sulfur-based VOC such as methyl mercaptan and the organic sulfides, while VFAs are fatty acids with less than 6 carbon atoms. VFAs are most commonly associated with the decomposition of carbohydrates and lipids (i.e. fats and oils) and include the recognisable acetic acid (vinegar).

Ammonia (NH_3) is an inorganic compound and it is the most significant nitrogen-based volatile associated with composting. It has a characteristic pungency which will be recognisable to many people through its presence in household chemicals and urine. Amines and indoles are other highly odorous organic N-based compounds.

Another inorganic gas that is sometimes featured in compost emissions but associated with anaerobic conditions, is hydrogen sulfide (H_2S), producing the familiar rotten egg smell.

Feedstocks with high protein content are particularly vulnerable to production of odorous compounds (Ma *et al.* 2013). Proteins are made up of amino acids, which upon degradation may release volatile nitrogen (amines and ammonia) and volatile sulfur (organic sulfides, mercaptans, and hydrogen sulfide) compounds. Feedstocks with high amine and protein content include poultry manure (0.56% dry weight (DW)), biosolids (0.3-1.2% DW), food scraps (0.4% DW), and some green waste depending on the source (0.3% DW) (Miller 1993).

The presence or absence of any of these compounds is a function of both the physicochemical characteristics of the feedstock, and the process conditions under which decomposition takes place.

VOSCs feature prominently in operations composting high-S containing feedstocks such a food waste, paper, gypsum, manure and biosolids (Miller 1993). While many VOSCs form under both aerobic and anaerobic conditions, they tend to accumulate under anaerobic conditions. For example, Homans and Fisher (1992) found that sulfurous compounds were generated mainly under anaerobic conditions during the thermophilic stage of composting when aeration was insufficient to meet oxygen demand.

Incomplete aerobic degradation processes also result in the emission of alcohols, ketones, esters and organic acids, mainly during the early stages of composting Homans and Fisher (1992). While VFAs can be associated with almost any feedstock, they are especially common when anaerobic conditions prevail (Haug 1993; Epstein 1997). Butyric acid is perhaps the most recognizable VFA since it is responsible for the characteristic “garbage” smell of rubbish bins.

Feedstock at composting plants is typically complex and highly variable. This is also reflected in the complexity observed when odorous emissions are investigated. Studying three of the largest food waste composting plants in Taiwan, Mao *et al.* (2006) detected a range of compounds including:

- hydrocarbons (pentene, hexene, benzene, toluene, ethylbenzene, styrene, p-xylene, o-xylene)

- ketones (acetone, butanone)
- esters (methylacetate, ethylacetate)
- terpenes (α-pinene, β-pinene, limonene, p-cymene)
- sulfurous compounds (dimethyl sulfide)
- nitrogenous compounds (ammonia, amines), and
- volatile fatty acids (acetic acid).

Of these compounds, the key substances detected at concentrations greater than their odour detection thresholds were ammonia, amines, dimethyl sulfide, acetic acid, ethyl benzene, and *p*-cymene.

Similarly, a study conducted in Spain, determined that the key emissions from the composting of the organic fraction of municipal solid waste (OFMSW) were aromatic hydrocarbons, ketones, hydrocarbons, terpenes, alcohols and volatile fatty acids (Delgado-Rodríguez *et al.* 2011). The key malodorous chemical groups contained nitrogen (mainly NH_3) or sulfur (mainly H_2S), amines, phenolic compounds, aldehydes, thiols (mercaptans), ketones, and alcohols.

Other work by Mustafa *et al.* (2017) showed that oxygenated compounds were produced in large amounts during the initial fermentation of food waste, while solvents, paints, and food additives in MSW are likely to generate aromatic compounds.

Fragrant detergents and green waste were found to be the likely sources of terpenes and hydrocarbons. Terpenes are aromatic compounds that contribute to the fragrance of many plants. They are therefore a major contributor to odour problems at green waste composting facilities (Defoer *et al.* 2002; Mustafa *et al.* 2017). Examples include limonene from lemons, cineole from *Eucalyptus* spp. and pinene from the resin of pine trees. Limonene was found to be the most represented terpene in an MSW plant in Italy (Scaglia *et al.* 2011), while Schiavon *et al.* (2017) detected *p*-cymene as the dominant VOC during OFMSW composting.

Bulking agents are typically used in many facilities processing odorous feedstocks to improve the physicochemical characteristics of a mix prior to composting (Epstein 1997). Common bulking agents used in MSW, biosolids and food waste composting plants include wood chips and green waste.

Although this practice typically reduces emissions associated with composting, bulking agents can contribute terpenes to the odour mix (Van Durme *et al.* (1992); Defoer 2002; Delgado-Rodríguez *et al.* 2011). The smell of terpenes may not be unpleasant at low concentrations but may become annoying as their concentration increases. They can also contribute to the overall unpleasantness of composting emissions when mixed in with other odorous compounds (CIWMB 2007).

Dimethyl sulfide, dimethyl disulfide, limonene and α-pinene were the most significant odorous VOCs at a wastewater sludge composting facility investigated by Van Durme *et al.* (1992). The latter two compounds were released from wood chips used as a bulking agent for the sludge. Delgado-Rodríguez *et al.* (2011) found that the terpenes, limonene and β-pinene, were present at relatively high concentrations compared to other VOCs in MSW composting.

Moreover, their concentrations were related to the C:N ratio of the initial mixes. Higher concentrations of limonene and β-pinene were detected in high and medium C:N ratio mixes, as compared to low C:N ratio mixes. In general, the highest emissions were observed in the early stages (thermophilic phase) of the processes and in the incoming materials as they were shredded. However, terpene emissions decreased in the first 15 days of the composting cycle, with β-pinene concentrations decreasing at a faster rate than limonene.

The design and operation of a successful composting plant is based on the optimisation of key process control parameters (aeration, particle size, C:N, moisture, initial pH) and minimisation of VOC and other odorous emissions. Studying relationships between these process control parameters (time, moisture, aeration, and C:N), temperature and chemical compounds in composting, Delgado-Rodríguez *et al*. (2011) concluded that the relative influence of these factors on selected VOCs followed the order:

C:N < moisture < aeration

Aeration had the strongest negative effect (i.e. higher values) on selected VOC emissions including the VOCs that were affected. In general, VOC emissions tended to increase with aeration, and diminish with increased moisture and C:N ratio.

Consequently, the authors suggested that to minimise emitted VOC and odours during composting of odorous feedstocks such as MSW organics, low aeration (remain aerobic; 0.05 L_{air} kg^{-1} min^{-1}), high C:N ratio (>50), and medium moisture (55%) may be a suitable strategy. Their findings agree with the study by Kuroda *et al.* (1996) of pig manure composting. They are also corroborated by those described by Smyth and Rynk (2004) in green waste composting where VOC emissions were inversely correlated with C:N ratio.

In many parts of Europe, mechanical-biological treatment (MBT) plants are employed, not to produce compost for beneficial land application; but to stabilise the organic fraction of MSW prior to landfilling in a process called ‘bio-stabilisation’ or to dry it through ‘bio-drying’ to produce waste fuels. There is only one MBT plant in Queensland (Cairns) and several others interstate in New South Wales and Western Australia. However, any study of odour generation from MBT plants is potentially relevant to composting of food scraps and other mixed feedstocks.

Scaglia *et al.* (2011) studied emissions from a MBT plant in northern Italy, identifying 147 VOCs from ten different chemical groups including aliphatic hydrocarbons, alcohols, esters, ketones, terpenes, furans, nitride, sulfide, aromatic hydrocarbons, and halogenated organic compounds. The VOCs in air emissions from the start of the composting process comprised (on a relative basis, i.e. %) aliphatic hydrocarbons (41 ± 12%), terpenes (31 ± 7%), ketones (11 ± 4%) and aromatic hydrocarbons (8 ± 6%).

Changes in the pattern of VOCs occurred through the composting process, specifically, during the active phase of the bio-stabilisation process. After 28 days of biological processing, emissions were characterised by the high presence of terpenes (67 ± 7%) and less of aromatic compounds (9 ± 4%). After 90 days composting, emissions comprised mainly of aromatic compounds (68 ± 24%) with marginal fractions of other VOCs.

Another interesting study by Schiavon et al (2017) compared volatile air emissions from three aerobically biodegraded waste matrices in a bench-scale experiment including dewatered biosolids, pre-digested OFMSW, and untreated food waste. In this study, detected VOC concentrations were combined with the VOC-specific odour thresholds to estimate the relative weight of each biodegraded matrix in terms of odour strength. No olfactometry was conducted, instead odour concentration was determined from ‘chemical odour units’ (COU) i.e. the product of the concentration of the odorous chemical compound and its odour detection threshold were aggregated to estimate the total odour concentration in COU. The analysis of the mass spectra of the samples revealed the major presence of terpenes (especially α-pinene, β-pinene, *p*-cymene and limonene), organosulfur compounds (dimethyl sulfide and dimethyl disulfide) and esters (ethyl isovaleric acids).

Dimethyl sulfide and dimethyl disulfide were the key odorants detected in the composted dewatered biosolids, with dimethyl disulfide comprising more than 97% of the species present in the effluent emissions after 16 hours when the concentrations were at their peak. Emissions associated with the pre-digested OFMSW were dominated by terpenes at peak concentrations after 16 hours of processing. Under such conditions, the most abundant VOC was *p*-cymene (accounting for about 73%), followed by limonene (21%). Minor contributions derived from β-pinene and α-pinene and the concentrations of all these species decreased in the course of the experiment.

Finally, the key volatile compounds in emissions associated with the aerobic composting of untreated food waste were limonene, dimethyl disulfide, α-pinene, β-pinene, *p*-cymene and ethyl isovalerate. Under such conditions, limonene was the most abundant compound (accounting for about 83% of the total VOC concentration), followed by dimethyl disulfide (approximately 11%) and equal contributions of α-pinene, β-pinene and p-cymene (2% each). This time interval corresponds to the maximum concentrations of the four terpenes. Ethyl isovalerate was detected only during the first 24 hours, reaching its maximum after 8 hours. The work also demonstrated the benefits of pre-treatment of potentially odorous feedstocks with anaerobic digestion prior to composting (discussed in more detail elsewhere in the report).

The mixed nature of MSW can result in emissions of some chemicals associated with synthetic materials and hazardous wastes. For example, xylenes, styrene and benzenes are probably related to the initial presence in MSW of plastic polymers and household chemicals (Pierucci *et al.* 2005; Mao *et al.* 2006; Staley *et al.* 2006; Scaglia *et al.* 2011). Scaglia *et al.* (2011) also identified halogenated organic compounds, represented by tetrachloroethylene (PCE) and 1-chloro 2-propanol. PCE is a solvent used for dry cleaning and has been classified as toxic chemical. 1-Chloro 2-propanol is used to manufacture propylene oxide and propylene glycol and then used to produce plastic polymer (e.g. polyurethane). 1-Chloro 2-propanol was reported to be a probable human carcinogen (Ashby, 1996). These compounds were mainly observed in air samples from the final stage of composting, which may be a function of their relative concentration due to airflow reduction and their difficulty to process.

As noted in 2.3.3, direct correlations have been observed between biological activity during composting and the degradation of many odorous compounds (Scaglia *et al.* 2011). Nevertheless, some compounds can be “stripped” from the compost matrix by the movement of air through it before these compounds have had time to be degraded.

The highest emissions of odorous compounds are typically found in the early stages of the composting process, either at start-up or during the thermophilic phase.

Feedstocks rich in easily degradable carbohydrates (e.g. potato culls, some food wastes) can be prone to alcoholic fermentation, particularly under anaerobic conditions (CIWMB 2007). Alcohols occur readily as organic molecules decompose, while ketones are produced from the bacterial oxidisation of alcohols (Widdel 1986), or else they may be released from plastic packaging (Staley *et al.* 2006). These VOCs as well as carbonyl compounds, esters, and ethers are usually degraded quickly during the initial start-up (mesophilic-thermophilic) phase of composting (Staley *et al.* 2006; Scaglia *et al.* 2011).

For example, Eitzer (1995) found that ketone reached higher values in the mesophilic phase with 2-butanone identified as one of the most significant odour-causing VOCs in composting processes. High undecane concentrations and other aliphatic compounds have also been detected in MSW, cooking oil and food packaging (Reineccius, 1991; Appendini and Hotchkiss, 2002; Delgado-Rodríguez *et al.* 2011; Scaglia *et al.* 2011). In a similar manner to the terpenes, concentrations of 2-butanone and undecane decreased during the first 15 days of composting (initial mesophilic and thermophilic stages) after which they were no longer detected (Delgado-Rodríguez *et al.* 2011).

Other compounds, such as the VOSCs (mainly dimethyl disulfide) are released during the thermophilic stage when oxygen becomes limited. Delgado-Rodríguez *et al.* (2011), for example, determined that after the thermophilic stage, a progressive decrease in dimethyl disulfide levels was observed and was negligible at the end of composting.

Ammonia (NH_3) forms when proteins, urea and other N-based compounds are degraded (CIWMB 2007). NH_3 is easily the most important nitrogen (N)-based odorous gas released during composting. The importance of NH_3 is related to its odorous characteristic, but also because a valuable plant nutrient (N) is lost with ammonia emissions, which undermines compost quality and value. The primary reason why NH_3 is emitted during composting is due to an excess of N present in the feedstock as noted in 2.3.2. Thus, high-N content feedstocks such as manure, biosolids, grass clippings and offal can result in problematic NH_3 emissions.

According to researchers at San Diego State University, NH_3 is rarely the cause of odour complaints that occur beyond a facility's boundary (CIWMB 2007). The authors proposed several reasons for this:

- Ammonia has a high odour threshold (i.e. it takes relatively high concentrations to be detected);
- The character of the odour (hedonic tone) is not particularly offensive to most individuals since many people are familiar with the smell of it, and;
- Citing Haug (1993), they state that ammonia tends to dissipate rapidly after it is emitted.

High nitrogen fecal material (manure, biosolids) also has a characteristic and unpleasant odour associated with the compound's indole and skatole produced from the bacterial decomposition of the amino acid tryotophan (Yokoyama and Carlson 1974).

Though hydrogen sulfide (H_2S) is not a particularly common problem in most composting operations, it can be a feature where gypsum-based products (such as plasterboard) or other high sulfur materials are included in the mix (Miller 1993). It is heavier than air and can accumulate in confined environments, raising the possibility of asphyxiation (CIWMB 2007). It tends to form in anaerobic stockpile conditions (Delgado-Rodríguez *et al.* 2011). Hydrogen sulfide produces an offensive odour at very low concentrations. Few field-based studies have implicated this compound as a primary offending odour (CIWMB 2007).

Pre-treatment of wet and odorous waste streams such as animal manures and some food processing wastes through processes like anaerobic digestion; has frequently been suggested as an effective means to reduce the odour potential of organic wastes by reducing the organic matter and providing a high degree of biological stability (Orzi *et al.* 2015). This is because when pre-digested organic waste streams are then composted; odour emissions are typically reduced.

Anaerobic digestion (AD) is well established in Australia for processing sewage sludges / biosolids, manures from piggeries and some other animal wastes. It is also gaining attention for processing of food and food processing residues with a number of plants commissioned in recent years. There is significant interest in AD in Queensland as a potential alternative to composting for wet or liquid, putrescible streams such as grease-trap and food processing waste. Composting has always been a cheaper option in Queensland but with the landfill levy, government funding for new infrastructure and potential regulatory shift towards enclosed processing of these odorous materials (e.g. under the Swanbank Temporary Local Planning Instrument, see Chapter 10); it is likely to become a viable alternative.

Schiavon *et al*. (2017) advanced this argument for biosolids and the organic fraction of MSW (OFMSW). As mentioned earlier, they determined chemical odour units (COUs) from the product of the concentrations of the odorous chemical compounds and their odour detection thresholds. While this type of approach is considered simplistic and indicative only, it suggested that when odour formation was at its maximum the waste gas from the composting of untreated food waste showed a total odour concentration about 60 and 15,000 times higher than those resulting from the composting of dewatered biosolids and the digested organic fraction of MSW, respectively. This could be relevant in the Queensland context when assessing the odour potential of biosolids that have been through some form of digestion process, versus those which have not.

While their odour assessment method is reliant on the accuracy of the odour threshold data and ignores the synergistic effects of the combinations of volatile compounds on odour generation, rather assuming single compounds found in abundance will dominate the odour's character and concentration, they identified a key odorous compound in each waste matrix studied.

Dimethyl disulfide (98% of total odour at maximum concentration after eight hours), limonene (61% of total odour at maximum concentration after 16 hours) and ethyl isovalerate (99% of total odour at maximum concentration observed after eight hours, while by contrast, the maximum VOC concentration was observed after 48 hours) were determined to be the highest contributor to odour for the dewatered biosolids, digested OFMSW, and untreated food waste matrices respectively. In regard to total odour concentrations from each matrix, untreated food waste (440,800 COU) shows the highest odour potential compared with dewatered biosolids (7,290 COU) and digested OFMSW (29 COU). The latter is considerably lower than the previous two, especially if compared with untreated food and green waste. Schiavon *et al.* (2017) considered that this is because food and green waste was the less stabilised waste matrix under investigation.

7.2 Measuring and quantifying odour in composting

As noted in 2.3, composting follows a series of steps requiring some form of 'process control'. It is important to understand which steps are likely to cause the greatest odour impact.

An odour emissions inventory tallies-up the number of odour units (OU) generated by specific odour sources. This is a function of:

- odour concentration, expressed in dilutions to threshold or odour units per cubic meter[11], as measured by dynamic olfactometry;
- total odour emission rate (ou.m^3/s) from a source based on
  - the product of the odour concentration (ou/m^3) and ventilation rate (m^3/s) from a point or volume source, or
  - the product of the odour concentration (ou/m^3) and ventilation rate (m^3/s) through a flux chamber or wind tunnel sampling system over an area source (m^2) (e.g. stockpile) to produce a specific odour emission rate (SOER, ou.m^3 m^{-2} s^{-1}) that is combined with the source's total surface area (m^2), or
- duration of odour generation.

Thus, an odour inventory helps to identify which odour control strategies should be prioritised by determining which sources contribute the largest percentage of odour emissions (ou.m^3/s) (Epstein and Wu 2000).

It is generally accepted that the critical period for peak odour concentrations are during the first 2 to 3 weeks of the composting process (Schlegelmilch *et al*. 2005). This is illustrated, for example, in Figure 18 for a study conducted by Schlegelmilch *et al*. (2005) for "biowaste" (food and garden organics, or FOGO in Australia) composting in Germany.

[11] Note: In the Australian standard (AS4323.3), ou/m3 was changed to ou, i.e. just odour units NOT odour units per cubic metre.

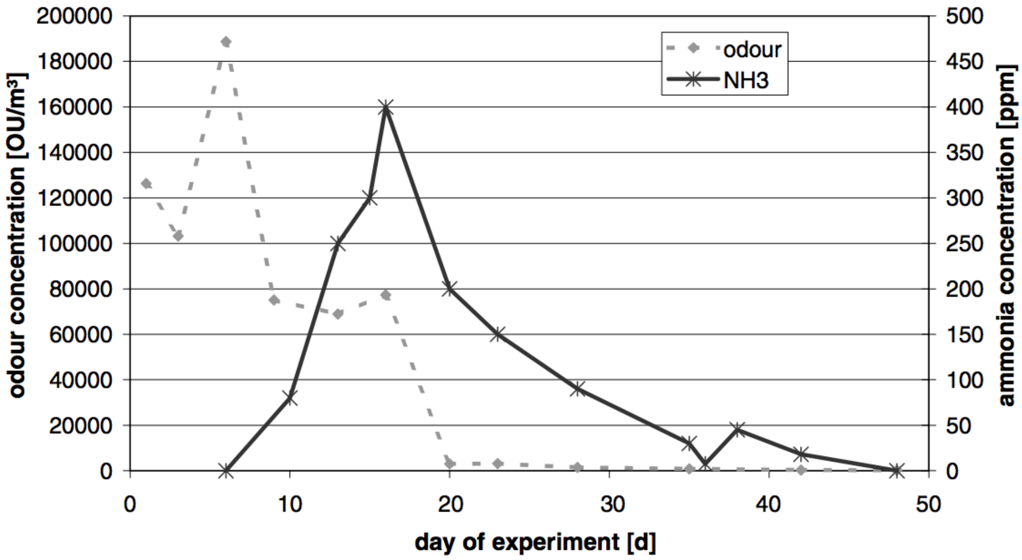

Figure 18 Odour (in odour units, OU/m3) and ammonia (ppm) concentrations at the exhaust air outlet of a composting reactor over a 7-week period (Schlegelmilch et al. 2005).

This makes sense because organic materials in the early stages of decomposition emit large quantities of natural and intermediate volatile compounds. Oxygen demand at this stage is also very high and there is increased risk that conditions could rapidly become anaerobic.

Sironi *et al.* (2006) performed odour balance studies on 40 representative Italian waste biological treatment plants. The study included facilities of different scales and type, processing both green waste and municipal solid waste (MSW)[12]. Emissions from single-process steps and whole of process emissions were determined and odour emission factors (OEFs) were calculated. An OEF is a representative value that relates the quantity of odour released to the atmosphere to a specific activity index, which may be for example the waste treatment capacity, the gross weight production, the site surface or a time unit. In their study, the OEFs were calculated as a function of plant capacity.

OEFs enable the estimation of the odour emission rate (OER) associated with a composting plant even before its construction, and they can be useful input data in odour dispersion models (Sironi *et al.* 2003, as cited by Sironi *et al.* (2006)).

Sironi *et al.* (2006) evaluated the following process steps:

- MSW receiving
- green waste receiving
- aerobic biological treatment (essentially thermophilic composting)
- curing
- finished product storage, and
- over-screen storage.

Firstly, there were no significant differences between the odour concentration values associated with equivalent process steps between plants, excepting waste receival and biological treatment. For this reason, the average odour concentration value for

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[12] In Europe, MSW composting is often called mechanical and biological treatment (MBT) in differentiation to source separated organic waste composting.

each of these process steps was calculated without distinguishing between green waste composting and MSW processing via mechanical-biological treatment (MBT) technology. The data also did not differentiate between closed or open composting facilities[13]. Their results are summarised in Table 6.

Table 6: Odour emission factors (OEFs) for MSW MBT and green waste composting plants in Italy (Sironi et al. 2006)

	Geometric mean of OEF (10^6 ou_E t^{-1})	Median of OEF (10^6 ou_E t^{-1})	% Deviation
Waste receiving	12.553	11.051	5.0
Green waste receiving	3.015	3.296	9.9
MSW aerobic biological treatment	139.948	127.042	6.1
Green waste aerobic biological treatment	12.501	5.248	12.2
Curing	39.943	29.946	7.4
Overscreen storage	2.424	3.196	12.0
Final product storage	7.536	9.247	8.3

The first thing to note is that the OEF associated with aerobic biological treatment of MSW (analogous to MSW composting) was an order of magnitude greater than any other process. Aerobic biological treatment accounted for about 69% of OEF_{tot} for MSW facilities. Secondly, the next major potential odour impact was associated with curing. The OEFs associated with curing were not significantly different between MSW and green waste facilities (Table 5). But, for green waste facilities, OEFs associated with curing were more than three times those of the thermophilic composting stage. Curing accounted for about 61% of OEF_{tot} at green waste composting facilities.

It should be noted that these OEF values were derived from process air sampled prior to any end-of-pipe odour treatment (e.g. biofilter). Now, the total odour emission rates (OER_{tot}) could be calculated for two or more facilities as a crude way of estimating potential odour impacts with or without a biofilter.

The following equation is used to calculate OER_{tot}:

$$OER_{tot} = Tp(OEF_{tot}) \dots \text{ Eq X}$$

where Tp is tonnes processed. OER_{tot} is expressed typically in Australia as ou per second (ou/s) and sometimes per year.

If a biofilter were considered, then the efficiency of odour control (Eff, as a fraction) would be factored into the equation. If, for example, a biofilter treated process air from the receival (rec) and composting (comp) areas, then Eq X above would be modified, thus:

$$OER_{tot} = Tp[(OEF_{rec} + OEF_{comp})(1\text{-}Eff) + OEF_{curing} + OEF_{overs} + OEF_{product}] \text{ Eq X}$$

[13] It did not evaluate odour off-site, or exhaust air after odour treatment. However, one could assume that the curing piles, overscreen storage and final product storage could, in many cases, be located outdoors.

Comparing two 50,000 tonne facilities processing green waste or MSW, both operating a biofilter at 90% efficiency, and using the input data from Table 6, the total odour emission rates for the facilities would be:

Green Waste $OER_{tot} = 50000[(3.02 \times 10^6 + 1.25 \times 10^7)(1-0.9) + 3.99 \times 10^7 + 2.42 \times 10^6 + 7.54 \times 10^6]$

$= 2.57 \times 10^{12}\ OU_E\ yr^{-1}$ or $8.15 \times 10^4\ OU_E\ s^{-1}$

MSW $OER_{tot} = 50000[(1.26 \times 10^7 + 1.40 \times 10^8)(1-0.9) + 3.99 \times 10^7 + 2.42 \times 10^6 + 7.54 \times 10^6]$

$= 3.26 \times 10^{12}\ OU_E\ yr^{-1}$ or $1.03 \times 10^5\ OU_E\ s^{-1}$

Of particular interest in this exercise is that it suggests that enclosing a green waste composting operation and treating emissions through a biofilter is unlikely to address the major odour sources. In fact, if the curing still takes place outdoors (as is typical), then the largest single source of odours – the curing piles - will not be affected by the biofilter.

In contrast, for MSW composting (and likely other similar high odour, high nitrogen content organics such as food waste), the use of enclosed composting with a biofilter could be very effective at reducing odour impacts since most of the odours are emitted in the composting phase itself, accounting for nearly 70% of OEF_{tot}.

It should also be noted that this is a pretty crude exercise. OERs do not say anything about the character and intensity of odours. Furthermore, there are many factors affecting odour dispersion from a composting site. Although new compost piles may not produce the highest number of odour units, the intensity of the odour generated may be higher because of the types of compounds formed during the early stages of decomposition (Coker 2012).

Higher intensity odours are also detectable at lower concentrations and therefore have a relatively higher potential to cause complaints.

Nevertheless, Sironi *et al.* (2006) are not the first researchers to identify curing piles as an important source of odours at some composting sites. Epstein and Wu (2000) found the same for windrow composting in the United States. They found that 27% of the odours were generated during composting, and 62% were from curing piles. The strongest concentration of odours was generated during turning but only for a short duration, as compared with the constant surface area source of large curing piles. As noted in 2.3.4, moving immature compost to curing piles too early can result in odours so this will vary depending on the maturity of compost in the curing piles. Often in MBT plants treating MSW organics and some other enclosed composting facilities, the compost is not very mature when it is moved to the curing stage.

These findings also accord with experience in Victoria. EPA Victoria reports that many of the problems that have plagued the recycled organics industry in Greater Melbourne over the years have been caused by excessive stockpiles of green waste compost accumulating at composting facilities (EPA VIC 2016).

Toffey *et al.* (1995) (cited in Epstein 1997) conducted a study to investigate odours from a biosolids aerated static pile composting facility. The mass of odours released from biofilters and curing piles were comparable, and in some cases greater, than the mass emitted from composting piles (aerated under negative or suction air flow). In part, the contribution of odors from the biofilter and curing piles were due to airflow patterns and the exposed surface area of these sources.

The major sources of odours at composting facilities can also be affected by seasonal changes. For example, in Taiwan, Mao *et al.* (2006) observed maximum emissions in summer (T= +30 °C) at the "tipping area" (where feedstock is received), suggesting that this was due to warm weather conditions and the acceleration of the composting process starting before material arrives at site. In winter (T= < 0 °C), maximum emissions were from the thermophilic composting and curing stages. Overall, total emission concentrations of identified volatile compounds were found to be higher in winter than in summer. Oxygenated compounds appeared to be the most dominant with ethyl alcohol as the major species, while others were relatively low in concentrations.

In the Queensland context, with a warm to hot climate, it is likely that the tipping area will be a major source of odours, particularly at facilities receiving waste that has already started decomposing and this will likely be heightened in the summer months.

The authors of the CIWMB (2007) odour study included an interesting discussion on odour sources. They state that:

> *'odour treatment devices like biofilters, and chemical scrubbers as well, can be relatively prominent contributors to site odour emissions, where they are used. This fact does not imply that they are ineffective, though poor design and operation would certainly increase the emissions. However, because exhaust air from piles, buildings and other enclosures is delivered to these treatment devices, they become points of concentration for odour emissions, even after they substantially remove and treat odorous compounds. At the same time, the odor emissions decrease from the other sources. In a sense the treatment devices become a point source of odours. This situation is especially true for scrubbers that discharge treated air through an exhaust stack (as opposed to the broad surface of a biofilter). Scrubbers, and even some biofilters, act like point sources of odour. Buildings and in-vessel exhaust outlets are other possible point sources. However, most other potential odour sources at a composting facility are considered area sources. Area sources emit volatile compounds over a broad area without a distinct and continuous air current (as in an exhaust stack). Emissions from area sources are more difficult to measure, quantify, predict and control. '*

Section 7 – key findings and recommendations

- Composting releases a complex mix of many different odorous compounds at different stages of the process and depending on the composition of the feedstock and process conditions. The compounds all behave and change differently as they travel through the atmosphere. Therefore, there is often little benefit in trying to trace odours by measuring specific isolated compounds in air.
- Most composting odours are associated with a range of different volatile organic compounds that are released, noting:
  - Feedstocks which are high in nitrogen are prone to producing ammonia gas during composting which has a recognisable pungent odour. Although ammonia has been noted to have a high odour threshold (i.e. it takes relatively high concentrations to be detected) and to dissipate rapidly.
  - Sulfur containing materials such as food, paper, gypsum, manure and biosolids can lead to release of mercaptans and other volatile organic sulfur compounds, while anaerobic conditions in a compost pile can lead to release of hydrogen sulfide gas with its characteristic rotten egg smell which is offensive even at low concentrations.
  - Feedstocks high in proteins such as food waste, manures and animal processing wastes are particularly vulnerable to production of odorous compounds as they can release both volatile nitrogen and sulfur based compounds.

Section 7 – key findings and recommendations

- Anaerobic conditions within a composting pile lead to formation and accumulation of particularly odorous compounds.

- On the other hand, pre-treatment of wet and odorous waste streams such as animal manures and some food processing wastes through processes like anaerobic digestion, has frequently been suggested as an effective means to reduce the odour potential of organic wastes. AD has generally not been a commercially viable alternative to composting for most streams in Queensland but that may change with upcoming changes such as the waste levy.
- Odour balance studies of composting facilities overseas, which measure the odour emission factors from different parts of the process have found that for high odour potential, rapidly biodegradable feedstocks (such as MSW organics) the main composting phase accounts for most of the odour emissions. For slower degrading materials such as green waste, the odour emissions are more evenly spread across the entire process from receival to final product storage. In both cases, the curing phase was also a significant odour source and this is consistent with other studies which have shown curing can be responsible for more odour release than the main composting stage.
- Weather has an impact and in Queensland's warm climate the tipping or receival area can be a major source of odours due to waste significantly decomposing before it arrives on site, which is less of an issue in colder climates.

Recommendations – Understanding odour

- Operators need to understand the composition of their feedstocks in order to understand the odour risk and implement proactive mitigation strategies. Operators should analyse feedstocks to assess key factors such as nitrogen and sulfur content.
- An odour audit or odour balance study can be a useful exercise to identify and quantify odour emissions from each stage of the process, resulting in an odour emissions inventory for the site. This will vary for each site but it is worth noting the receival area and curing piles can be major odour sources, in addition to the mixing and composting stages.

8 ODOUR TREATMENT TECHNIQUES

As noted above, it is difficult to capture odours from an open windrow composting operation, and it is generally necessary to capture odours to apply any kind of treatment techniques. In open windrow systems, odour management needs to focus on avoiding the generation of odours and minimising their impact on the community. Nevertheless, there are treatment techniques that can be applied to manage and reduce odours in windrow and enclosed systems.

Odour treatment systems can be broadly categorised into three groups:

- **Biological systems** use microorganisms to breakdown odorous gases in the process air exhaust of composting, by the use of systems such as biofilters, biotrickling filters and bioscrubbers (Kennes and Veiga, 2010).
- **Physical systems** strip odorous compounds out of exhaust air through physical processes like condensation, adsorption and absorption.
- **Chemical systems** use a designated reaction to change the nature of an odour into a less offensive chemical form.

The sections 8.1, 8.2 and 8.3 below discuss in more detail the biological, physical and chemical strategies available to treat odours as they are generated in a well-managed aerobic composting system. These could be applied to a range of composting technologies ranging from turned windrows and covered aerated static piles (with aeration running in negative pressure or sucking mode), to tunnel or bunker composting systems.

8.1 Biological systems

Biofiltration is the most common type of odour treatment technology used in composting systems. In basic terms, a biofilter is a bed of biologically active organic material through which the odorous air from compost passes through in order to trap and treat odorous compounds.

The simplest form of biofilter is a cap of matured compost on top of a windrow can also act as an in-situ “biofilter”. According to Coker (2012), compost caps were ‘developed in California primarily to reduce odour emissions but it became quickly apparent that they were potentially a method to reduce the volatile organic chemical precursors of ground-level ozone (smog)’.

He recommends a compost cap consisting of 50 to 100-mm of screened compost, or 150 to 200-mm of unscreened compost or coarse material. He also cautions that they can be ‘tricky to install properly’, since a cap that is too finely-screened or one that accumulates near the base of the windrow, can block air flow and starve the windrow of oxygen.

Figure 19 Visual comparison of emissions from an uncapped windrow (LHS) versus a capped windrow (RHS) from California (Buyuksonmez, 2011)

Buyuksonmez (2011) also found that although compost capping on windrows might impede airflow resulting in an increase in methane (CH_4) emissions, they were highly effective at reducing VOC emissions (a 61% reduction was measured).

In other work by San Diego State University researchers, the use of finished compost as capping or as “inoculum” in the compost mix, yielded the most consistently beneficial results in controlled studies (CIWMB 2007). In addition to finished compost, various other odour-mitigation alternatives were compared including, misting with water, odour-masking agents and two chemical treatments (a proprietary ‘oxygen release compound’ and hydrogen sulfide applied topically to the feedstock). Finished compost (as either inoculum or capping) was used in every trial with a range of different feedstocks, whereas the other agents were used only when appropriate to the odour group being targeted. The finished compost treatments were found to be particularly effective for controlling terpenes, ammonia and reduced sulfur compounds. It was noted that the compost used as a capping becomes part of the compost blend after turning. Their results clearly suggested that the compost capping treatment continued to have a beneficial effect on emissions after turning as it was then incorporated into the compost mix.

More commonly though, biofilters are typically associated with enclosed, forced aeration systems. In most cases, biofilters are open to the atmosphere, but they can also be enclosed in a reactor.

Biofiltration is a biological system of odour treatment because the bed of substrate in the biofilter houses the microorganisms that do the work to oxidize odorous compounds. Bacteria and fungi are the two dominant microorganism groups in biofilters (Kennes and Veiga, 2010), but secondary decomposer organisms like protozoa, amoebae and nematodes also play an essential role by recycling nutrients and balancing the system, by feeding on the bacterial and fungal biomass.

In a similar manner to the process of decomposition described earlier for composting, the oxidation of odorous compounds takes place in the biofilm that surrounds compost particles in the biofilter (Figure 20). The biofilm contains the microorganisms that degrade the pollutant.

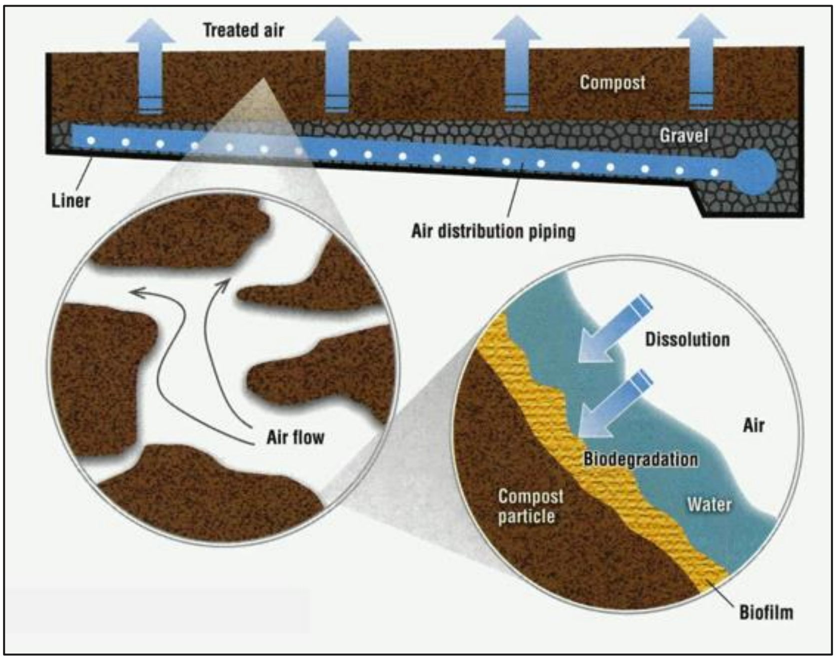

Figure 20 Cross-sectional representation of a fully engineered biofilter (Coker 2012)

In fully engineered biofilters, air is introduced into a plenum beneath the biofilter media. The plenum can be in the form of perforated pipes or a supported false floor with perforations, at the base of the unit. These pipes can be embedded in gravel or another porous material, acting both as an air plenum to distribute the exhaust evenly through the bed and as a barrier to keep fines from the organic layer above from clogging the pipes (Coker 2012). The biofilter media, up to 2-m deep, lies on top of the gravel. Alternatively, a solid, mesh-like floor can be supported on pillars to form a plenum, on which the biofilter media is placed. The depth of media is calculated to ensure that the gas retention time (known as the Empty Bed Residence Time, EBRT) is of sufficient duration, about 45 seconds to 2 minutes, to degrade the odorous compounds (Rosenfeld *et al*, 2004; Coker 2012).

The most important performance parameters for the proper functioning of biofilters are humidity, pH control and retention time of the air in the media (Bindra *et al* 2015).

The air stream can have a drying effect on the media, so some type of humidity control system is generally required (Schlegelmilch *et al* 2005). The most effective way of controlling biofilter inlet air moisture content to prevent the media from drying out is through humidification with a humidifier, supported by a sprinkler system on top of the biofilter. In the tropics, heavy rainfall can force operators to cover their biofilters (Accortt *et al* 2001).

The degradation of sulfur-containing odour compounds in the media can cause acidification, having a detrimental effect on microbial activity and the longer-term functioning of the biofilter. Some type of acid buffering capacity is generally required through addition of lime or calcium carbonate otherwise frequent media replacement may be required due to acidification (Bindra *et al* 2015).

The most common biofiltration medium is finished compost. Research comparing different biofiltration media has shown that wood-based filtering materials perform less satisfactorily compared to compost or peat (Mudliar *et al* 2010). Wood chips have low pH-buffering capacity, low specific surface area and low nutrient content compared to compost and peat. Nonetheless, wood chips can be effectively used as structural support (bulking agent) for active layers of peat or compost. Similarly, soils are sometimes used as biofilter material, but their efficacy is additionally compromised by low air permeability (Nelson and Bohn 2011), as it is with peat.

In composting a mixture of biosolids and green waste, Hort *et al* (2009) found the main odorous compounds at the 5th day of composting to be volatile organic sulfur compounds (VOSCs) with a total concentration of 3.28ppmv and ammonia (NH_3) at a concentration above 70ppmv. VOSCs are typically responsible for 80–90% of odours emitted during composting of biosolids due to their very low detection thresholds (FNDAE 2004).

Hort and co-workers passed the exhaust air from composting through an experimental biofilter (flow rate 15 m^3 h^{-1}; retention time 60 seconds). The biofilter was comprised of mature compost derived from the same materials being composted (i.e. biosolids and green waste). They found close to 100% removal efficiency for ethanethiol, dimethyl sulfide and dimethyl disulfide irrespective of the inlet mass loads. For NH_3, the mean removal efficiency was 94% (Hort *et al* 2009). High rates of ammonia-removal efficiency in biofiltration systems are common across the published literature, depending somewhat on the concentration of NH_3 in the exhaust gas being treated (Table 7).

Table 7: Comparison of published data on removal efficiencies for ammonia in biofilters (adapted from Hort et al 2009)

Authors	Bed media	Acclimation time (day)	EC	RE (%)	EBRT (s)
This study	Compost SS/YW	0	2.52 g NH3 m^{-3} h^{-1}	94	60
Galera et al. [58]	Rock wool-compost	nd	6.44g NH3 m^{-3} h^{-1}	78.6	63-132
			12.05 g H2S m^{-3} h^{-1}	68.1	
Pagans et al. [61]	Mature compost	0	8.29g NH3 m^{-3} h^{-1}	98.8	86
			7.17 g NH3 m^{-3} h^{-1}	95.9	
			61.3gNH3 m^{-3} h^{-1}	89.5	
			21.7g NH3 m^{-3} h^{-1}	46.7	
Kapahi and Gross [62]	Compost, oyster shells and perlite	nd	10.6g NH3 m^{-3} h^{-1}	96.4	nd
Gao et al. [63]	Compost-like biomass mixture	nd	0.18g H2s m^{-3} h^{-1}	98.9	46
Lau et al. [11]	50% mature compost + 25% screened compost + 25% soil	nd	4.33g NH3 m^{-3} h^{-1}	95	55
Schlegelmilch et al. [64]	Screened yard waste compost	7	4.37 g NH3 m^{-3} h^{-1}	100	80
Liang et al. [8]	Compost and activated carbon	15	0.02-0.391g NH_3 kg^{-1}media day^{-1}	95-99.6	31.9-79
Pinnette et al. [9]	Compost, bark mulch, wood chips	nd	1g NH3 m^{-3} h^{-1}	nd	nd
Taghipour et al. [5]	Compost, sludge, hard plastics	10	9.85 g NH3 m^{-3} h^{-1}	99.9	60
			9.44g NH3 m^{-3} h^{-1}	99.9	>30
Chen et al. [27]	Compost	1	12 g NH3 m^{-3} h^{-1}	97-99	60

*nd: not determined

An interaction sometimes occurs between NH_3 in the biofilter inlet air and the production, and/or the degradation, of hydrogen sulfide (H_2S) and mercaptan (methanethiol). Hort *et al* (2009) appeared to show that H_2S and mercaptan was only degraded when the concentration of NH_3 exceeded 30ppmv. They reasoned that the nitrogen requirements of microorganisms specific to the biodegradation of volatile organic sulfur compounds (VOSC) were probably not met below NH_3 concentrations of 30ppmv.

Various other interactions between odorous compounds have been reported in the literature with respect to the efficiency of biofilters. Due to the complex nature of compost emissions, chemical reactions can sometimes occur during treatment in biofilters that actually increase the concentration of sulfur-based odorous compounds (e.g. Goodwin *et al* 2000). Furthermore, the presence of H_2S has been reported to inhibit VOSC degradation in some cases (Hirai *et al* 2000).

Where some pollutants like H_2S and some VOCs cannot be reliably and economically handled through a standard biofilter set-up, a biotrickling filter can be considered. A biotrickling filter consists of a synthetic or naturally inert filter bed, over which an aqueous solution is trickled (Barbusinski *et al* 2017). As the air to be treated is carried through the filter bed, continuous irrigation with the aqueous solution supplies the essential nutrients needed for the microorganisms to grow. The pollutant to be treated is initially absorbed by the aqueous film that surrounds the biofilm and biodegradation then takes place (Mudliar *et al* 2010). This system can reportedly handle difficult applications with greater efficiency because process conditions in the aqueous solution are easier to control compared to the complex organic matrix of a standard biofilter (Ramírez *et al* 2009; Barbusinski *et al* 2017).

A biofilter can also be successfully combined with a bioscrubber acting as a humidifier of exhaust air before it reaches the biofilter for final treatment. Bioscrubbing is a process of biological waste gas treatment in which exhaust air is ‘‘washed’’ in an absorber with a scrubbing liquid. The scrubbing liquid is subsequently drawn off and transferred to an activation tank in which the constituents absorbed to the liquid are degraded by microorganisms. The liquid is continuously cycled through the process (VDI 3478 1996[14]). Schlegelmilch *et al* (2005) found that the addition of a bioscrubber buffered the high malodor concentration in the inlet gas flow of their biofilter. On its own, the bioscrubber resulted in a 28% degradation efficiency of VOCs, but in combination with a screened compost biofilter, total degradation efficiency increased to 99%.

In summary, for turned windrow applications, a simple compost capping or the use of finished compost as “inoculum” in the feedstock mix can be very effective for odour control.

For enclosed systems, biofiltration generally has a high odour removal efficiency, moderate capital cost, low operational and maintenance cost, good reliability, low chemical usage and produce virtually no waste by-products (Bindra *et al* 2015). Biofilters are not particularly effective in industrial applications treating high concentration air streams but are ideally suited for implementation in organics processing facilities (where there are high volumes to be treated with low concentration of odorous compounds). However, they do occupy a large space, which is somewhat of a disadvantage in urban-industrial areas where they are most likely to be employed.

8.2 Physical systems for treating odours

The simplest forms of physical systems for odour control involve spraying water or fine mist over compost windrows, especially prior to or during turning events. The delivery of water as a fine mist is most effective as it increases the surface area for interaction between the water droplet and the odour compound. In these systems, the odour compound is absorbed into the volume of the water droplet (Coker 2012). Buyuksonmez (2011), for example, investigated this effect and found that volatile organic compound (VOC) emissions from windrows were reduced by 19% by watering for 20 minutes prior to turning.

Another simple example of a physical system is associated with the use of covered compost systems. Condensation of water is commonly found on the underside of a compost cover. Odorous gases are trapped by this layer of condensation allowing them to be degraded there or after dripping back into the compost pile.

Many other physical approaches have been proposed based on the principle of adsorption. These methods show great promise, if they could be implemented in an economical fashion.

Adsorption is the deposition and adhesion of one chemical (the odorant) onto the surface of another medium (Coker 2012) such as activated carbon, wood ash or biochar. To be effective, adsorption media must have a very high surface area and porosity. Activated carbon, for example, is commonly used for retention of various pollutants due to its high surface area (in the range of 500–1500 m^2 /g), porosity and surface chemistry (Bandosz and Petit 2009).

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[14] As cited in Schlegelmilch *et al.* (2005).

Rosenfeld *et al* (2002) reported that windrows amended with 12.5% and 25% high-carbon wood ash by volume reduced odour emissions by some 73% and 88%, respectively. Reductions in emissions were noted for VOCs, and most ketones and aldehydes. The high pH (about 10.3) of wood ash is a potential problem, but exposure of the ash to rainfall and atmospheric CO_2 was reported to reduce the pH to around 8.6. Nevertheless, wood ash amended windrows reported higher ammonia emissions (presumably a result of the high pH amendment).

Others have reported that activated carbon is not necessarily suitable for removal of ammonia gas (Bandosz and Petit 2009). When it comes to biochar, performance efficiency with respect to ammonia retention appears to depend on the raw materials used to make the biochar, and processing conditions (Wang and Zeng 2018). Steiner *et al* (2010) mixed biochar with poultry litter prior to composting and found that the NH_3 concentration in emissions was reduced by up to 64% and total N losses by up to 52%. Biochar has also been known to increase temperature rise and NO_3-N concentration during composting and decrease pH and NH_4^+ content (Wang and Zeng 2018).

Awasthi *et al* (2018) investigated different dosage rates of biochar on volatile fatty acids (VFAs) and odour generation during biosolids-wheat straw composting in enclosed reactors. It was found that amendment with 8–12% biochar reduced the concentration of VFAs, and odour generation compared to the unamended control, particularly during the first 20 days of composting. Total bacterial abundance and the abundance of VFA-degrading bacteria were also higher in biochar-amended treatments. The authors concluded that co-composting with biochar improved the physicochemical properties of the compost mix leading to improved conditions for the growth of VFA-degrading bacteria.

The use of zeolite has frequently been proposed for controlling NH_3 losses during composting. Zeolite is a highly porous mineral of volcanic origin that has a very high ion-exchange capacity. Bernal *et al* (1993) used zeolite to trap NH_3 emissions released from a composting mix of pig slurry and straw. It was proposed that zeolite could be effectively used as a compost cover. Others have used zeolite as a component of the compost mix, sometimes in combination with biochar and other amendments. Biochar plus lime was found to increase the nutrient content of compost by reducing NH_3 and N_2O emissions (Awasthi *et al* 2016a). In another study, 12% biochar plus 10% zeolite reduced NH_3 losses by 58–65% when they were co-composted with dewatered fresh sewage sludge (Awasthi *et al* 2016b).

In concluding, the use of high-C adsorbents like biochar or other highly porous media like zeolite has shown to be an effective option for managing odours. However, responses vary depending on what is composted, composting conditions and the type and characteristics of the adsorbent used.

Furthermore, questions remain about the economic viability of the use of these products compared to alternative approaches to odour control. Some studies investigated the use of adsorbents in compost mixes in which the physicochemical characteristics had not been optimised (raw manures, for example). While these types of studies have merit from a research perspective, optimising the physicochemical characteristics of the mix will continue to be critically important for the vast majority of commercial composters.

8.3 Chemical systems for treating odours

Chemical approaches to odour control focus on oxidisation or on breaking the carbon-hydrogen-oxygen bonds to change the chemical structure of odorous compounds (Coker 2012). Other formulations sequester, or bind, odorous chemicals like amines, ammonia and sulfur compounds, whilst others are used as masking agents.

Chemical scrubbing is a common odour control system used in industrial applications. In this application, exhaust-gas compounds are dissolved in a scrubbing liquid with chemicals added which react with the dissolved waste gas compounds to neutralize them. Besides ozone (O_3) and hydrogen peroxide (H_2O_2), sodium hypochlorite (NaOCl) is sometimes used because it is both relatively cheap and easy to handle (Schlegelmilch *et al* 2005). Their effectiveness depends greatly on selecting the right solvent for the job.

Packed beds or columns are frequently used to increase the surface area available for contact between the reagent and odour compounds. The packing material, an inert plastic or ceramic compound for example, can be housed in a vertical tower or horizontal structure (Gabriel *et al* 2004). The air stream is pumped through the packing material, and a chemical solution is sprayed into it to react with the odour compounds. In fine mist wet scrubbers, the chemical solution is sprayed as micron-sized droplets (Lang *et al* 2000), increasing the surface area of the contact solution to improve odour absorption efficiency. Some systems re-circulate the solution until it is used up and has to be disposed of. In others, the chemical solution is not re-circulated and there is a continuous waste discharge (Bindra *et al* 2015).

Bindra *et al* (2015) conducted a technological and life cycle assessment of different odour control technologies for implementation in organics processing facilities. The technological assessment compared biofilters, packed tower wet scrubbers, fine mist wet scrubbers, activated carbon adsorption, thermal oxidisation, oxidisation chemicals and masking agents. Comparisons were made on a variety of operational, usage and cost parameters. Based on the technological assessment it was found that biofilters and packed bed wet scrubbers were the most applicable for organics processing facilities. Based on factors such as capital, operational and maintenance costs, system flexibility and ease of operation, the biofilter systems had an advantage over the other systems in this comparison. However, the LCA showed that a packed-bed (with chemical solution re-circulation) was found to be a superior system from the perspective of environmental impact. The authors found that the main environmental impact associated with the biofilter set-up was the energy intensity of running the fan systems.

Iron III chloride ($FeCl_3$) has long been used as a chemical flocculant/coagulant for wastewater (Adlan *et al* 2011) and as an acidifying agent in organic waste treatment (Yuan *et al* 2015). Flocculation/coagulation and acidification processes can both assist in odour control. In wastewater treatment, charged NH_4-N particles are neutralised during coagulation with addition of $FeCl_3$ and are subsequently adsorbed onto floc surfaces. Acidification of alkaline waste streams in solid waste treatment (composting and anaerobic digestion) through the addition of $FeCl_3$ can reduce NH_3 losses by altering the balance of the organic N mineralisation pathway towards the accumulation of ammonium (Boucher *et al* 1999).

Yuan *et al* (2015) used a combination of cornstalks (as bulking agent) and $FeCl_3$ pre-treatment of food waste to control odours produced during composting. Whilst the cornstalks had a limited effect on NH_3 losses, hydrogen sulfide (H_2S) emissions were reduced by 61%. $FeCl_3$ was found to be more effective for ammonia removal – H_2S emissions were reduced by 61% and NH_3 by 38%. Using cornstalks and $FeCl_3$ in combination resulted in 42% less NH_3 and 76% less H_2S during composting than pure kitchen waste. An interesting feature of this study was the use of $FeCl_3$ with food waste, which is typically acidic (pH 5.1-5.3). Over the course of 28 days composting, the pH rose to around 8, while the C:N ratio was reduced from 20-25:1 to about 13-15:1. The authors claimed that the reduction in NH_3 losses could be attributed to NH_4^+ becoming “fixed by being coagulated with $FeCl_3$”.

Struvite, or magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4.6H_2O$), is a mineral that often precipitates from wastewater during anaerobic digestion when ammonium (NH_4^+), phosphate (PO_4^{3-}), and magnesium ions (Mg^{2-}) are present (Miles and Ellis 2000). Struvite has been implicated in the scaling of heat exchangers and piping, deposits in seafood canning, as well as the formation of kidney stones (Miles and Ellis 2000 and references therein). However, struvite precipitation is also of potential interest in composting as a means of conserving nitrogen and reducing losses of ammonia gas (NH_3).

Mg and P salts precipitate ammonium ions (NH_4^+) into struvite crystals via the following reactions (Wang and Zeng 2018):

1. $NH_4^+ + PO_4^{3-} + Mg^{2-} + 6H_2O <> MgNH_4PO_4.6H_2O$
2. $NH_4^+ + HPO_4^{2-} + Mg^{2-} + 6H_2O <> MgNH_4PO_4.6H_2O + H^+$
3. $NH_4^+ + H_2PO_4^- + Mg^{2-} + 6H_2O <> MgNH_4PO_4.6H_2O + 2H^+$

In applying struvite precipitation to conserve nitrogen in food waste compost, Jeong and Kim (2001) found that the NH_4^+ salt content of compost reached 1.4% of dry mass, which was 3–5 times higher than that in the untreated control. Scanning electron microscopy and energy dispersive X-ray spectroscopy confirmed the formation of struvite crystals during the composting process. Subsequent work (Jeong and Hwang, 2005) estimated that the theoretical maximum conversion of initial N content into ammonia was in the order of 33–36%. However, the high doses of Mg and P salts needed to achieve complete precipitation caused adverse effects on decomposition. But, dosage of Mg and P salts to convert around 20% of the total nitrogen still resulted in substantial reductions of ammonia loss without any adverse effects to the composting process.

The application of struvite precipitation has also been applied to pig manure, poultry manure, other agricultural waste streams, and even termite mounds (Karak *et al* 2015; Wang and Zeng 2018). Fukumoto *et al* (2011) found that the addition of phosphoric acid (H_3PO_4) and magnesium chloride ($MgCl_2$) or magnesium hydroxide ($Mg(OH)_2$) to pig manure not only reduced NH_3 emissions but also other nitrogenous emissions except nitrous oxide (N_2O). Using a combination of calcium dihydrogen phosphate ($Ca(H_2PO_4)_2$) and magnesium sulfate ($MgSO_4$) as amendments in composting pig manure, Jiang *et al* (2016) significantly decreased both NH_3 (59%) and methane (CH_4) emissions by 59% and 65%, respectively.

Wang and Zeng (2018) reported that the main drawback with struvite precipitation is the high concentration of soluble salts that accumulate in the compost after treatment. To overcome this problem, Wang *et al* (2016) added lime together with struvite salts. This had no impact on struvite formation and the salinity of compost was reduced to less than 4.0 mS cm^{-1}. In addition, the inclusion of zeolite with struvite salts has also shown promise in reducing NH_3 emissions whilst keeping the electrical conductivity within acceptable limits (Chan *et al* 2016).

Finally, odours at composting facilities can sometimes be concealed by the use of masking agents. They can be dispersed into the air in a mist, on the surface of windrows or into the exhaust air stream. Their efficacy is debatable since the presence of masking agents can actually contribute to an odour nuisance, and furthermore, independent information can be hard to come by because many of these products are patented (Coker 2012).

In one study, San Diego State University tested four unnamed ‘odour neutralizing agents’ (ONAs) against samples of different feedstocks held in passively aerated containers. In this study, the efficacies of the ONAs were either non-effective or inconclusive, except for one product that was effective for control of reduced sulfur compounds. As such, the use of chemical odour neutralising agents to control odours from a composting facility is not recommended – it is unlikely to be effective and could potentially contribute to the odour nuisance.

In summing up this section on odour control technologies, we could not do better than to quote Craig Coker:

> *‘Few issues in the management of composting facilities will draw more attention, require more time or cost more dollars than managing odour problems. While there are a wide variety of engineered odour control technologies in the marketplace today, most composters would agree that*

> *simple is better. A well-designed and operated biofiltration system, coupled with good process design, good process and operational management, and attention to operational details will keep odour problems from becoming off-site public relations disasters'* (Coker 2012).

Emerging technologies that warrant further research, development and demonstration include the use of finished compost as capping or inoculum, and additives such as biochar (and other high-C materials), zeolite and Fe, Mg and P salts to improve odour control and compost quality (e.g. from conservation of N). It must be stressed that these approaches are not realistic alternatives to focusing on optimising the physicochemical properties of the mix prior to composting – they should rather be considered as a secondary line of defence.

Section 8 – key findings and recommendations

- It is difficult to apply odour treatment techniques to open windrow composting but one option which has been found to be effective is to apply a 'cap' of matured compost (up to 150-200mm thick if unscreened) on top of a newly formed windrow. The layer acts as a biofilter and can be very effective at reducing VOC emissions. After the first turning, the mature compost gets mixed into the compost where it acts as an inoculum and continues to have a beneficial impact.
- Where process emissions can be captured, such as in an enclosed or covered system or an aerated static pile operating in suction mode, the odours can be effectively treated through an engineered biofilter. Biofilters provide a high rate of odour removal efficiency for a moderate capital cost and low operating costs.
- Wet scrubbing systems can be used to treat particularly strong odorous air streams, often as a pre-treatment to a biofilter.
- Other physical and chemical treatments are available but have experienced limited application or success on composting facilities.
- Chemical masking agents have been used at composting facilities but their efficacy is debatable and they can actually contribute to the odour nuisance.

Recommendations – Understanding odour

- Composters processing odorous materials in open windrows should be encouraged to experiment with caps of mature compost as a measure to reduce odour emissions during the initial stage of composting.
- Engineered biofilters are a very efficient and cost effective method of treating odours if they can be captured from an enclosed or forced aeration composting system. They could similarly be applied to treat air from an enclosed feedstock receival and mixing building.

9 APPROACHES TO ODOUR REGULATION

This section reviews relevant Australian and international legislation on odour regulation, management and impact criteria. It is intended to provide an overview of the various approaches to odour regulation and impact assessment for waste management and composting facilities, and how they compare with other odour generating industries.

The regulation of odour and assessment of odour nuisance is approached in a variety of ways throughout the world. Jurisdictions typically adopt the approach to promulgate regulations based on standardised odour methodologies and objective criteria or use the principles of Nuisance Law to regulate the management of odour episodes. These standardised methods can be classified as follows:

30. **Maximum impact standard** – comparison of ambient odour concentration and individual chemical statistics against impact assessment criteria.
31. **Separation distance standard** – application of fixed and variable distance buffers to separate odorous activities from sensitive land uses.
32. **Maximum emission standard** – application of a source maximum emission rate for mixtures of odorants and individual chemical species.
33. **Maximum annoyance standard** – assessing the number of complaints received or the annoyance level determined via community surveys.
34. **Technology standard** – requiring use of best available technologies (BAT) to minimise odour emissions.

The most commonly applied impact assessment technique is to use odour emission rates, given by the odour concentration multiplied by the volume flow rate of the source and simulation of topographic and meteorological data of the site to estimate the odour dilution in the surrounding environment using dispersion modelling (Nedham and Freeman, 2009).

Odour concentration predictions made by dispersion models can then be assessed against odour impact criteria, which are commonly formed by three components (Sommer-Quabach et al., 2014):

- Odour concentration threshold
- Percentile compliance level and
- Averaging time.

To account for dispersion model predictions based on hourly mean concentrations that may mask peak odour episodes experienced by the human nose that occur in seconds, peak-to-mean ratios are commonly used to assess short-term exposure (Schauberger et al., 2012a).

In some jurisdictions, nuisance assessment of existing odorous activities is regulated by ambient odour measurement techniques. This can comprise human odour patrols that evaluate observed odour strength against dilution to threshold (D/T) limits measured by field olfactometry or in terms of the perceived intensity of the odour.

9.1 Appropriate Location of Composting Facilities

Chapter 2.3 identified a number of key process and operational measures to reduce odour production through optimisation of the composting process, to suit the feedstock being processed. This section reviews guidance developed by other jurisdictions around appropriately locating composting facilities to manage odour impacts.

NSW EPA (2004) has published recommendations that are used to identify optimal locations for composting facilities, or assess the suitability of a proposed site. NSW

NSW EPA recommends that composting facilities be located away from residences or other sensitive receptors due to high potential to cause odour and other nuisances. The impacts and necessary odour management approaches will depend upon:

- The size of the composting area
- The category of the organics to be composted
- The composting technology employed
- Whether the composting process is enclosed or open-air
- Whether odour removal technology is employed
- The estimated odour emission rate
- The topography of the site
- The direction and frequency of winds
- The distance of the facility from the property boundaries.

NSW EPA (2004) recommends that judicious location of the processing site is perhaps, the most effective way of dealing with the potential negative and to some extent inevitable, impacts of composting on local amenity. Careful design and selection of process components and equipment, as well as good operating techniques, procedures and staff training, are other important ways of minimising amenity problems but may not be fully successful in all situations.

Due to the odorous nature of composting operations most Australian jurisdictions define some form of minimum separation distance between the composting site and its closest sensitive receptors. The separation distance is the minimum allowable distance between the composting facility and any nearby sensitive land uses such as residences, schools or heath facilities.

Different terminology applies across jurisdictions. Victoria and Queensland use the term “separation distance”, whereas South Australia has “evaluation distances” and Tasmania has “attenuation distances”. The term “buffer distance” has also frequently been used in the past to describe separation distances.

Regardless of terminology, separation distances are adopted in recognition of the fact that even the best managed facilities, which may feature state-of-the-art odour control technologies and operational measures, may still at times release unintended odour emissions which travel beyond the site boundary.

Buffer distances are not an alternative to providing appropriate control of the emission source, but to protect the receptor amenity from accidental or unforeseen emissions that may occur due to issues such as equipment failure, human error, accidents and abnormal weather conditions. The separation distance is therefore intended to be a risk management tool (one of many), which manages unexpected or accidental odour emissions from a site such as a composting facility. Whilst ensuring an appropriate degree of separation between an odour source and its closest sensitive receptors will to some extent mitigate odour nuisance arising from normal site operations, it is not considered appropriate to rely solely on separation distances as the primary odour mitigation measure.

NSW EPA notes that an appropriate separation distance from any work or storage area of the site to the nearest residence, public building or business is crucial. As such, it is incumbent on the proponent to undertake the necessary analysis, which may include odour modelling, to identify a suitable separation distance and/or other control measures to demonstrate that the selected site is appropriate.

Each jurisdiction applies separation distances between different points. The Environment Protection Authority Victoria (EPA Victoria) utilises two separate methods for describing separation distances: “Method 1” and “Method 2”.

EPA Victoria considers Method 1 (as illustrated in Figure 21) to be most appropriate as it calculates the distance between the property boundary of the facility and that of the sensitive use. This therefore provides the facility emitting the odour with the freedom to use any location within their site for odourous activities. It also denies them the ability to use non-odourous sections as part of their attenuation zone. Method 1 most frequently applies in the vicinity of residential areas and sensitive land use zones.

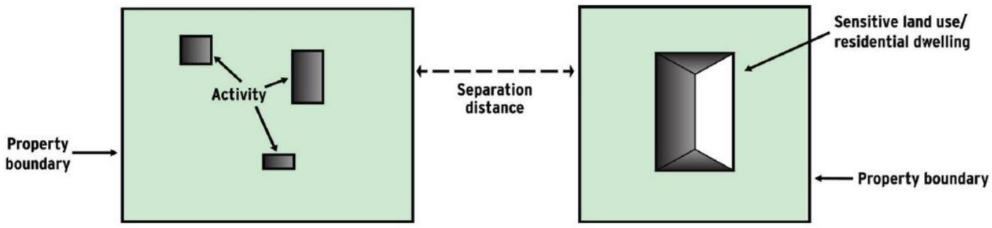

Figure 21: Calculation of separation distance using Method 1 (figure from EPAV, 2017, p. 8)

EPA Victoria allows Method 2 to be used provided it can be justified. It is considered to be acceptable in sparsely populated areas where there are only a few sensitive receptors located outside of a sensitive land use zone. Under this method, the separation distance is measured from the activity boundary, which is an imaginary line within the site boundary enclosing all activities, plant and buildings where residual odour emissions may occur. The separation distance extends from the activity boundary, beyond the sensitive land use boundary to the sensitive land use or residential dwelling itself as shown in Figure 22. Given the use of the activity area, Method 2 may only be used when it is certain that the activity area will not change.

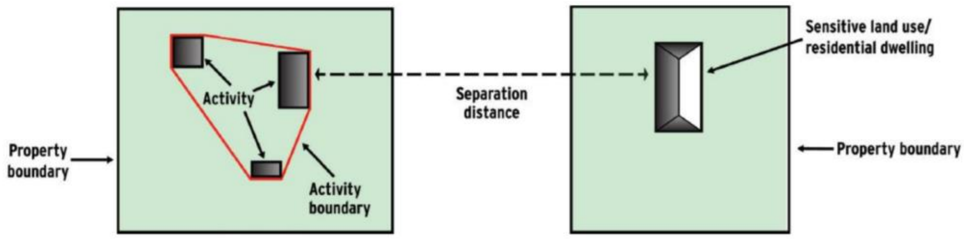

Figure 22: Calculation of separation distance using Method 2 (figure from EPAV, 2017, p. 8)

Further, EPA Victoria provides guidance on separation distances for two different types of composting “reference facilities”. Reference Facility 1 accepts green waste, vegetable organics and/or grease trap waste for composting. The feedstock is received in the open air, however aerobic composting occurs within an enclosed area with odour capture and treatment facilities. Composted materials are subsequently allowed to mature in the open air. In contrast, Reference Facility 2 accepts only green waste, which is received, processed, and matured in the open air within turned windrows.

In Victoria, separation distances are developed by selecting the most similar reference facility to the proposed composting facility and applying the appropriate throughput. The resultant distance is given as a guide only and assumes predominantly flat or slightly undulating topography and a standard range of meteorological conditions. If the separation distance cannot be met, it may be adjusted on the basis of adding further control measures to the plant design and operations.

Western Australia and South Australia also indicate separation distances for composting facilities. South Australia recommends a 500 m buffer for green waste composting in a 'one size fits all' approach, offering no adjustment for facility size or context. For composting of any other organic wastes, EPA suggests that a suitable buffer will be determined on a case by case basis. Presumably, an odour impact assessment study would be required to support the application, and this would form the basis for determining the required separation distance.

Western Australia provides separation distances for a range of composing technologies and feedstocks; however, plant size is not factored into the distance calculation. Of particular note is the significantly lower buffer for green waste composting (of 150 m) compared to Victoria (between 600 and 2,000 m based on processing capacity) and South Australia (500 m).

A summary of recommended separation distances in different Australian jurisdictions is provided below, for different annual throughput ranges and processing technologies in (Table 8).

Table 8: Composting separation distance guidelines in Australia

Technology being used	Types of feedstock	Size of facility	Recommended separation distance (metres)	Reference
Open air receival, Enclosed aerobic composting with secondary odour capture and treatment, Open air maturation	Green waste, Vegetable organics, Grease inceptor trap waste	1,200 tonnes per annum	>300	EPA Victoria: Table 2 from EPA Victoria, 2017, p. 9 Reference facility 1
		14,000 tonnes per annum	>500	
		36,000 tonnes per annum	>800	
		55,000 tonnes per annum	>1,000	
		75,000 tonnes per annum	>1,200	
		90,000 tonnes per annum	>1,400	
Open air receival, Open turned windrow, Open air maturation	Green wastes	1,200 tonnes per annum	>600	EPA Victoria: Table 3 from EPAV, 2017, p. 9 Reference facility 2
		14,000 tonnes per annum	>1,100	
		36,000 tonnes per annum	>2,000	
		50,000 tonnes per annum	>2,000	
Outdoor uncovered, regularly turned windrows	Manures, mixed food/putrescible, and vegetative food waste	Not specified	1,000	WRC, Local Government, DoE License or Registration Category 67A,
	Biosolids		500	
	Green waste		150	

Technology being used	Types of feedstock	Size of facility	Recommended separation distance (metres)	Reference
Outdoor covered, turned windrows	Manures, mixed food/putrescible, and vegetative food waste	Not specified	750	WA EPA, (2005) Appendix 1.
	Biosolids		250	
	Green waste		150	
Outdoor covered windrows with continuous aeration,	Manures, mixed food/putrescible, and vegetative food waste	Not specified	500	
	Biosolids		250	
	Green waste		150	
Enclosed windrows with odour control	Manures, mixed food/putrescible, and vegetative food waste	Not specified	250	
	Biosolids		150	
In-vessel composting with odour control	Manures, mixed food/putrescible, and vegetative food waste	Not specified	150	
	Biosolids		150	
All technologies	All Feedstocks	>200 t/y	1,000	SA EPA, (2016) Appendix 1, p.29.
		>20 and <200 t/y	300	
		<20 t/y	100	

9.2 Odour regulation approaches

Odour impact criteria in Australia vary widely as each state has the autonomy to develop its own policy, management and assessment approach. Notwithstanding this, the environmental legislation in most states manages the effects of odour pollution in terms of environmental harm, which includes environmental nuisance.

The foundation of each state's odour impact assessment approach is based on dispersion modelling. Several models are approved for use by the regulators including the United States EPA approved steady state Gaussian plume model AERMOD, the Gaussian puff model CALPUFF (a former US EPA approved model for long range transport > 50 km and complex terrain and coastal applications), and the Australian CSIRO developed Eularian grid model TAPM.

The steady state Gaussian plume model AUSPLUME, developed by EPA Victoria in 1986 but not maintained since its last update in 2004, is no longer supported as a regulatory model in most states, with Victoria replacing AUSPLUME with AERMOD in 2014. Modelling-based odour impact assessment criteria typically comprise a maximum odour concentration limit, a peak-to-mean factor for adjusting the averaging period from standard hourly model predictions to peak concentrations that align with human nose response times, and a percentile statistic for addressing extreme model outliers or matching predictions to odour complaint data. Remarkably, each of these criteria components is different from state to state.

Concentration assessments are generally made at the nearest existing and future off-site sensitive receptor with the exception of Victoria and Tasmania, where the assessment is made at the fence line, and at and beyond the boundary respectively.

There is also a variety of alternative and supporting assessment approaches that include risk assessments, source-specific odour intensity adjusted concentration criteria, field ambient odour intensity surveys, odour diaries and community odour surveys.

9.2.1 Queensland

Air quality in Queensland is administered by the Department of Environment and Science under the *Environmental Protection Act (1994)* (EP Act) and its subordinate legislation including the *Environmental Protection Regulation (2008)* and *Environmental Protection (Air) Policy (2008)* (Air EPP). Under the EP Act (1994)(s3.14), environmental harm is defined as:

1. "Environmental harm is any adverse effect, or potential adverse effect (whether temporary or permanent and of whatever magnitude, duration or frequency) on an environmental value, and includes environmental nuisance.
2. Environmental harm may be caused by an activity —
3. whether the harm is a direct or indirect result of the activity; or
4. whether the harm results from the activity alone or from the combined effects of the activity and other activities or factors."

While environmental nuisance is defined as EP Act (1994)(s3.15):

> *"Environmental nuisance is unreasonable interference or likely interference with an environmental value caused by —*
>
> *a) aerosols, fumes, light, noise, odour, particles or smoke; or*
>
> *b) an unhealthy, offensive or unsightly condition because of contamination; or*
>
> *c) another way prescribed by regulation."*

The Air EPP identifies the environmental values of the state to be enhanced and protected and sets out the indicators and air quality objectives for enhancing and protecting the environmental values. The indicators for protecting the environment include air pollutants that may cause harm to the health and biodiversity of ecosystems, human health and wellbeing, the agricultural use of the environment and the aesthetics of the environment. Included in the list of indicator pollutants are key odorous compounds (hydrogen sulfide, carbon disulfide, formaldehyde, styrene, tetrachloroethylene, toluene) with air quality objectives based on odour thresholds for protecting the aesthetic environment (or annoyance from odour). Notwithstanding this, odour criteria are not provided in the Air EPP (2008).

The management and assessment of odour is addressed in the Guideline: *Odour Impact Assessment from Developments 2013* (EHP, 2013), which sets out dispersion modelling-based odour impact assessment criteria for new developments. These criteria are based on a default annoyance threshold of 5 ou for predicted 1-hour average odour concentrations and take into consideration peak odour impact based on near nose response times using conservative peak-to-mean factors (F[15]) of 10:1 for wake-free stacks and 2:1 for ground-level sources or wake-affected stacks:

- 0.5 ou, 1-hour average, 99.5th percentile for wake-free stacks;

[15] *F* refers to the Peak-to-Mean factor used to convert hourly model prediction to short-term average peak odour concentrations.

- 2.5 ou, 1-hour average, 99.5th percentile for ground-level sources and wake-affected stacks.

The 99.5th percentile value is intended to be used as a statistical measure to filter extreme values generated by modelling and not meant to be interpreted as allowing nuisance or failure of emission controls (EHP, 2013). Furthermore, the guideline states that the criterion is not intended to be "a 'pass' or 'fail' benchmark for dispersion model odour estimates, rather guidance can be derived from the estimates on likely impacts which can then be further refined through consideration of such things as the observed impacts of similar facilities, the sensitivity of the receiving community and 'offensiveness' of the odours likely to be emitted. Proponents must first ensure that their proposals incorporate best practice environmental technology to minimise odours in a manner consistent with the management hierarchy under the EPP (Air)." (EHP, 2013)

The EHP (2013) guideline states: "Odour impact assessments need to reflect the levels of exposure that result in nuisance in communities affected by the odour impact. The odour impact assessment for a new facility or for modifications to an existing facility needs to be conducted for the purposes of achieving an environmental outcome, which meets a typical environmental authority condition for odour such as:

> *"There must be no release of noxious or offensive odours or any other noxious or offensive airborne contaminants beyond the boundary of the site that causes environmental harm at any odour sensitive place."*

The guideline also recommends a range of other assessment approaches for existing facilities for which the community has registered odour complaints. For instance, assessing odour impacts by:

- Comparing dispersion model predictions against an impact criteria concentration equivalent to an intensity value of weak (or distinct in some cases) on a source by source basis, as determined in the laboratory on source odour samples by the method described in the German VDI3882.1 (1992) standard,
- Field ambient odour intensity surveys based on the methods described in the German VDI3940 (1993) standard (note, this standard was amended as VDI 3940.1 (2006) and 3940.2 (2006) and VDI3940.3 (2010)),
- Community odour surveys to understand the experience of the local population in relation to environmental impacts,
- Odour diaries, where selected individuals within a community are requested to keep a log of odours experienced in the area,
- Odour complaint analysis, and the
- Compliance history of the facility.

9.2.2 New South Wales

Odour management in NSW is legislated under the Protection of the Environment Operations (POEO) Act 1997, with guidance on its application provided in the Technical Framework: Assessment and management of odour from stationary sources in NSW (2006) and the accompanying Technical Notes: Assessment and management of odour from stationary sources in NSW (2006).

Odour impact criteria and additional specific information on the modelling and assessment of odour mixtures and individual odorous compounds are detailed in the Approved Methods for the Modelling and Assessment of Air Pollutants in NSW (2016a).

The framework sets out three levels of odour impact assessment for new, modified and existing activities, regardless of whether the sources are classified as point or fugitive (diffuse) and depending on the individual characteristics of the development and its location, (NSW EPA, 2006a). The assessment levels are defined as:

- *Level 1 is a screening-level technique based on generic parameters for the type of activity and site. It requires minimal data and uses simple equations to provide a broad estimate of the extent of any odour impact. It may be used to assess site suitability and odour mitigation measures for new or modified activities.*
- *Level 2 is a screening-level dispersion modelling technique, using worst-case input data (rather than site-specific data). It is more rigorous and more realistic than a Level 1 assessment. It may be used to assess site suitability and odour mitigation measures for new, modified or existing activities.*
- *Level 3 is a refined-level dispersion modelling technique using site-specific input data. This is the most comprehensive and most realistic level of assessment available. It may be used to assess site suitability and odour mitigation measures for new, modified or existing activities.*

Two types of ground-level concentration exposure limits are provided for the assessment of odour: individual and easily identifiable odorous compounds from point sources, and complex mixtures of odour from point and fugitive sources. Ground-level concentration criteria for odorous compounds are selected based on the most stringent of odour and health related impacts. Impacts are reported using an averaging time of an hour at the 100th percentile (maximum) concentration value for Level 2 and 99.9th percentile concentration for Level 3 impact assessments.

Ground-level odour concentrations are assessed against population density-based impact assessment criteria between 2 and 7 ou on the basis of nose response time (i.e. approximately 1 s). Concentrations are calculated for the 100th percentile value for Level 2 and 99th percentile concentration for Level 3 impact assessments. Although an averaging time of the order of 1 s is stated, in practice modelling is undertaken using a 3-min averaging time. This is due to the peak-to-mean factors (F) applied being dependent upon the type of source (e.g. area, line, surface wake-free point, tall wake-free point, wake-affected point, volume), atmospheric stability (i.e. Pasquill-Gifford classes) and distance downwind of the source (near or far-field). For instance, peak-to-mean factors applied are:

- Area sources
    - F = 1.9 applies to E, F stability classes in the far-field (F = 2.3 in the near-field), and
    - F = 2.3 for A-D stability classes in the far-field (F = 2.5 in the near-field);
- Volume and wake-affected point sources
    - F = 2.3 for A-F stability classes in the near-field and far-field.

The peak-to-mean factors apply in an idealised situation in flat terrain with the receptor situated along the plume centreline, with no plume meandering or influence from obstacles or terrain features. The population-dependent variable odour criteria recognise the possible spread in olfactory sensitivity of the general population. Larger groups of people, therefore, have a greater probability of containing individuals with higher sensitivity and consequently, the risk of adverse effects is higher requiring more restrictive criteria. The odour criteria are applied at the nearest existing and future off-site sensitive receptor. Cumulative emission impacts associated with other similar odour generating facilities nearby should also be considered in the assessment.

9.2.2.1 Regulatory Composting Guidance

The NSW *Composting and Related Organics Processing Facilities Guideline* provides advice concerning the planning and consultation process, site selection and environmental factors to consider in an Environmental Impact Statement (EIS) for composting facilities. In addition to outlining the regulatory framework, it identifies benchmarks to measure and monitor performance and possible environmental management techniques. While it is only a 'guideline', it is the primary reference for regulators when assessing licensing applications and applicants would need to justify if they wish to pursue methods outside the guidelines.

In the section 'Guidelines for Satisfying Environmental Objectives', the document identifies 13 key environmental issues, including odour management. This section details design requirements for dealing with odour issues and ensures that both the design of the facility and the operating procedure do not cause offensive odours outside the premises.

The guideline also includes a categorisation system according to feedstock risks, as presented in Table 9 below. When considering and developing conditions for Environment Protection Licensing under the POEO Act, the NSW EPA refers to the categorisation system. Three categories are defined as follows:

- Category 1 organics are likely to have the lowest potential environmental impact
- Category 2 organics are likely to have a moderate impact
- Category 3 organics have the greatest potential to seriously affect the environment and amenity.

These categories are used and referred to in several sections that outline preferred methods of minimising odour impacts.

Based on the categorisation of organic material, the section '*using the categorisation of incoming organics to select appropriate equipment*' discusses the best treatment method available for various materials.

- Category 1 organics: open-air methods for composting have generally been found to be satisfactory, provided that the materials being processed (especially grass clippings, weeds and leaves) are not allowed to become anaerobic
- Category 2 organics: open-air methods for composting are satisfactory with strict feedstock preparation and operating controls. Category 2 organics are best processed in enclosed facilities but if the intention is to use an open-air facility to compost Category 2 organics then the operator will need to demonstrate that the location, design, operating methodology and resources of the facility will prevent odorous emissions
- Category 3 organics: similarly, enclosed facilities are recommended and the applicant would need to demonstrate that the location, design, operating methodology and resources of any alternative technology would prevent odorous emissions and degradation of the local amenity.

Whilst there are open windrow facilities in NSW that process Category 3 organics (i.e. food waste), they are legacy facilities or quite remote, and it is generally considered within industry, that any new facility processing food waste would need to use enclosed composting technology.

Table 9. Categorisation of organics

Potential to have environmental impact	Organics	Types of organics permitted in categories[1] (Categories with larger numbers may contain types from classes with smaller numbers)	
		Type	Examples of organics
Lowest Potential environmental impact	Category 1	Garden and landscaping organics	Grass[2]; leaves; plants; loppings; branches; tree trunks and stumps.
		Untreated timber	Sawdust; shavings; timber offcuts; crates; pallets; wood packaging.
		Natural organic fibrous organics	Peat; seed hulls/husks; straw; bagasse and other natural organic fibrous organics.
		Processed Fibrous organics	Paper; cardboard: paper-processing sludge; non-synthetic textiles.
Greater potential environmental impact than Category 1, less potential impact than Category 3	Category 2	Other natural or processed vegetable organics	Vegetables; fruit and seeds and processing sludges and wastes; winery, brewery and distillery wastes; food organics excluding organics in Category 3.
		Biosolids[3] and manures	Sewerage biosolids, animal manure and mixtures of manure and biodegradable animal bedding organics.
Greatest potential environmental impact	Category 3	Meat, fish and fatty foods	Carcasses and parts of carcasses; blood; bone; fish; fatty processing or food.
		Fatty and oily sludges and organics of animal vegetable origin	Dewatered grease trap; fatty and oily sludges of animal and vegetable origin.
		Mixed residual waste containing putrescible organics	Wastes containing putrescible organics, including household domestic waste that is set aside for kerbside collection or delivered by the householder directly to a processing facility, and waste from commerce and industry.

Notes:
1. These categories are used only to facilitate reference to these groupings of waste and organics (with different potential environmental impacts) in these guidelines and in environmental protection licences; they are **not** used in waste legislation.
2. Particular care should be taken when grass clippings are present in the feedstock. It is well known that careful process management is required to mitigate odour and leachate problems when processing grass clippings (e.g. Buckner 2002). High moisture content, high nitrogen levels, abundance of readily available organic matter and poor structure and tendency to mat mean that grass can easily become anaerobic and odourous.
3. Conditions applying to processing and use can be found in *Environmental Guidelines: Use and Disposal of Biosolids Products* (EPA 1997).

The guideline suggests the following for process controls:

- There should be immediate attention to potential odorous organic loads, such as rapidly biodegradable organics;
- Rapidly biodegradable organics should be covered, and the quantity of such material exposed to the atmosphere should be kept to a minimum;
- Rapidly biodegradable organics of food and animal origin should be stored in moisture- and vermin-proof bins; and
- Records of complaints about odours should be kept, and they should be correlated with weather conditions and deliveries of categories of organics.

The guideline also outlines the preferred practices for storing odorous materials, suggesting that:

- The quantity of cured organics stored at the facility should not be greater than 18 months' worth of production;
- The quantity of Category 1 organics awaiting processing should not exceed 10% of the currently utilised facility processing capacity (tonnes/year);
- The quantity of Category 2 and Category 3 organics awaiting processing should not exceed one day's production, unless it is stored in a manner that prevents the release of odours; and
- Rapidly biodegradable organics should be prepared into processing feedstock as soon as they are received, or no later than by the end of the day of receipt or otherwise should be placed either; into an enclosed storage containers or sheds fitted with exhaust air purifiers or covered with a 15-centimetre-thick layer of compost that is in the curing stage.

9.2.3 Victoria

Victoria's general odour criterion for new or expanded industrial sources of 1 ou, 99.9th percentile for a 3-min averaging time, applied at and beyond the property boundary, can be considered the most stringent in Australia. However, for industries encompassing intensive animal husbandry production, to ensure beneficial land uses are protected, a multi-criteria approach is adopted based on dispersion modelling, a more relaxed performance criterion, use of an environmental risk assessment and consistency with integrated land use planning e.g. broiler farms set within a rural zone.

The dispersion of odour emissions is modelled, with predicted maximum concentrations at the facility's boundary not to exceed 5 ou, 99.9th percentile for a 3-min averaging time. In most cases, dispersion modelling is conducted using EPA Victoria's regulatory model, AERMOD, however in special cases where coastline and complex terrain effects are likely to influence plume transport, and with the permission of EPA, more complex models such as CALPUFF and TAPM may be used.

Where the modelling-based assessment criterion is not met, the use of an odour environmental risk assessment is required. In this regard, the utilisation of a risk matrix is recommended rather than the use of a single criterion (EPA Victoria, 2001; EPA Victoria, 2012; ERM, 2012). Hourly model predictions are converted to a 3-min average using a constant peak-to-mean factor of F = 1.82, based on the use of Turner's power law using an exponent of 0.2. Odour emissions from nearby sources of the same type must also be included in the dispersion model for a cumulative odour impact assessment.

New proposals must demonstrate that best practice management of their emissions will be applied (Brancher *et al* 2017). For individual chemical compounds that are odorous, specific design criteria are established on the concentration at the odour detection threshold of the substance (CASANZ, 2013, cited in Brancher *et al* 2017).

9.2.3.1 Regulatory Composting Guidance

The EPA Victoria guide to *Designing, constructing and operating compost facilities* outlines what EPA Victoria considers to be best practice design and operation principles for compost facilities in Victoria. It is restricted to aerobic composting processes only and does not cover other common methods such as anaerobic digesters, dehydrators, and vermicomposting.

The scope of the document is advisory only and not the source of any mandatory legal requirements, however it contains information and recommendations for meeting the relevant legislative requirements for composting in Environment Protection (EP) Acts and State Environment Protection Policies (SEPPs).

In assessing work approval applications, the EPA will consider a variety of conditions, including the following:

- Historical compliance performance for existing sites;
- Limits on tonnage of waste that can be received;
- Use of best practice technologies;
- The enclosing of part or all the composting process and use of appropriate odour controlling technologies;
- Minimum separation distances to sensitive land uses; and
- Discharges to land or surface water.

In obtaining an Environmental licence, the EPA will usually set conditions, including the below:

- No detection of offensive odour beyond site boundary;
- No discharge of nuisance particles beyond site boundary; and
- No discharge of waste, wastewater or litter to land, groundwater or water environments.

Continuous odour sources are identified as:

- Raw organics if they have begun to decay;
- The stockpiling of the product;
- The breakdown of organic matter generates volatile organic compounds (VOCs) which can be highly odourous; and
- Contact water and leachate.

Discontinuous odour sources can include:

- Machinery (material stuck to surfaces or wheels);
- Turning/aeration during the mixing and preparation phase can generate odour; and
- Screening and movement of feedstock and compost.

The design and operation of a compost facility will affect odour emissions and whether it complies with SEPP (AQM) objectives. The following are recommended measures in which compost facilities can use to meet the SEPP (AQM) requirements:

- Fit and maintain appropriate odour control equipment, such as biofiltration;
- Develop and implement an odour management plan, which monitors;
  - an inventory of all sources of odour;
  - odour sources and controls under normal conditions;
  - odour monitoring and recording regime;
  - odour management during upset conditions; and

  - routine maintenance of odour control equipment (where installed).
- Create a balanced compost recipe that enables appropriate levels of oxygen, temperature, carbon/nitrogen ratio and pH levels; and
- Train staff to prepare and process material according to best practice.

The below table summarises the recommended appropriate technologies dependent on the feedstock category and the chemical contaminant limits for unrestricted use.

Table 10. Victoria - Recommended technology types

Feedstock category	Recommended technology requirements		
	Open environment	Enclosed or covered environment	Enclosed with secondary odour control
1: Lowest potential risk of harm to human health and the environment	Yes	Yes	Yes
2: Medium potential risk of harm to human health and the environment	Yes	Yes	Yes
3: Medium to high potential risk of harm to human health and environment	No	Yes	Yes
4: Highest potential risk of harm to human health and the environment	No	No	Yes

9.2.4 International Odour Regulations

The project team has reviewed odour regulations and impact assessment criteria in various countries and jurisdictions around the world. The review focused on odour measurement techniques, the assessment of impact and nuisance including methods such as dispersion modelling and their related odour impact criteria, legislative instruments, odour management and control measures. Detailed summaries of the regulations in each jurisdiction are contained in Appendix A and inform the summary discussion below.

Of particular note is that the European Union recently updated its Best Available Techniques Reference Document (BRef) which applies to a range of waste treatment facilities (new and existing) including composters. In the EU, the BRef documents feed down into permitting conditions in individual countries. Existing facilities are given four years to comply with the new standards. It sets a number of standards around enclosure of treatment facilities, covering or windrows, controlling key process parameters and monitoring of waste input characteristics. It also specifies limits on air emissions including odour, VOCs and ammonia.

9.3 Summary of odour regulations

Odour impact criteria vary significantly between jurisdictions. Criteria may be based on assessments using the following techniques:

- Atmospheric dispersion modelling,
- Field ambient odour surveys,
- Separation distances, and
- In-stack concentrations and source characteristics.

Criteria based on atmospheric dispersion modelling methods can vary widely due to differences in:

- Concentration limits, which may be set according to:
  - Detection threshold (i.e., 1 ou),

  - Receptor olfactory sensitivity as a function of population density,
  - Individual odorous compound detection threshold (depending on the compound of most interest),
  - Intensity of the odour at concentrations above detection threshold, and
  - Hedonic (or offensiveness) characteristics of different odours above detection threshold.
- Percentile statistics, which account for:
  - Exposure frequency,
  - Model outliers (e.g., the maximum prediction is based on the 99.9th percentile statistic of a year of hourly predictions rather than the 100th percentile), or
  - To correlate with odour complaint records.
- Averaging periods that may be selected based on:
  - Duration of tolerable/intolerable odour exposure,
  - Average exposure to odour over an hour, which typically coincides with model time intervals,
  - Peak exposure – typically 1-second (nose response time) to 3-minutes,

Criteria set on field survey methods may be based on:

- Ambient odour intensity measurements on a subjective ranking scale,
- Ambient hedonic odour tone measurements on a subjective ranking scale,
- Ambient odour intensity measurements in ‘sniffing units’ to determine the plume’s horizontal extent,
- Dilutions-to-threshold (D/T) units, which are similar to an ‘odour unit’, based on field olfactometer measurements

Dispersion model and field survey criteria can also be based on predicted or observed concentrations or intensity rankings at and beyond the facility’s boundary or at the nearest existing and future off-site receptor.

Separation distance criteria can be set according to:

- Facility size or annual processing capacity,
- Feedstocks processed, and
- Composting process technology, and
- Odour control type.

Source design criteria and in-stack concentration limits may include:

- Odour concentration limits,
- Individual odorous compound concentration limits,
- Stack flow conditions (e.g. exhaust gas velocity and stack diameter), and
- Minimum stack height conditions

Each approach has inherent value, but it is recommended that a mix of criteria are used. This is important as no single criteria approach utilises all of the FIDOL factors to assess odour nuisance (Balch, 2015). In addition to setting impact assessment criteria for a facility as part of the conditions of its Environmental Authority, it is recommended that conditions of process operations be placed on the activity that are proven to effectively achieve the odour conditions in the community such as controls on feedstock storage and blending; windrow mixing and turning; maintaining aerobic conditions; and monitoring of key process parameters.

Section 9 – key findings and recommendations

- Most other jurisdictions provide clear guidance in varying forms about acceptable locations for new composting facilities and particularly, separation distances to minimise amenity impacts on residents and sensitive receptors. Such guidance is helpful to operators and developers of new projects but is not a substitute for site specific assessment of the risks, through an odour impact assessment. The separation distance needs to factor in the local topography and climate, types of materials being processed, the technology and other engineering and operational controls in place.

Recommendations – Approaches to Odour Regulation

- The composting industry in Queensland could benefit from clear guidance produced by DES, on aspects such as locating composting facilities, separation distances, process and operational controls to minimise odour issues. Guidance documents from other states provide examples which may be considered, but the guidance should be tailored to Queensland context, be risk-based and allow a degree of flexibility for low risk applications.

10 SWANBANK COMPOSTING CASE STUDIES

As part of the Phase 1 investigations for this study, the project team reviewed two major composting facilities currently operating in South East Queensland and developed detailed case studies of their operations. The sites are in or near the Swanbank precinct which is host to a number of major waste facilities that play a significant role in managing waste from across South East Queensland and further afield.

The precinct has a long history of nuisance issues which have become more prominent and acute in recent years, due to factors such as encroachment of residential development. This led the Government to establish the Swanbank Odour Abatement Taskforce, among other actions.

The purpose of the case studies was to identify and understand the key issues facing those facilities and the Queensland composting industry more broadly. It is not being suggested that those facilities are representative of other composting facilities across Queensland, nor that all composting facilities face the same unique challenges as the Swanbank sites. Nevertheless, there are lessons that can be drawn from studying these facilities that can potentially be applied more broadly, whilst acknowledging the differences across the industry.

In undertaking the case studies, the project team consulted extensively with the two operators and we thank both companies for their openness and willingness to support the study.

The detailed information was provided by the operators in confidence and is commercial-in-confidence. As such, the case studies have been detailed in a separate report which is attached as Appendix B but is **not for public release. It is to be treated as strictly confidential.**

The two facilities studied account for around one quarter of the total organics processing capacity in South East Queensland (SEQ) and play a critical role in keeping organics out of landfill, take green waste from a number of councils across SEQ, process difficult waste streams from businesses and industry and produce compost products which improve soil quality.

Both use a very similar open windrow composting process where shredded green waste is mixed with a range of other organic wastes in liquid, solid and slurry from. As noted in Chapter 4, the list of feedstocks processed by Queensland composters is extensive and varied, and the same applies to both of these sites. One of the facilities is also licensed to process a range of inorganic and regulated waste via composting (under ERA 55), while the other is constrained to processing organic materials in line with ERA 53 requirements.

In both facilities, the green waste provides the carbon needed for the composting process and acts as an absorbent and bulking agent to allow processing of other high moisture and liquid materials, of which grease-trap waste and food processing residues are the most prominent. This is a common approach amongst composters in SEQ and elsewhere but not representative of all Queensland composters.

In both cases, the highest risk activities from an odour generation perspective were identified as:

- The raw materials receival and blending areas, where liquid wastes are received and temporarily stored, then blended with green waste. In particular, grease-trap and food processing wastes were identified as odorous feedstocks.
- The composting process itself – fugitive emissions from windrows and emissions during windrow turning activities, and
- The leachate storage ponds

Based on the review of the two facilities, a number of common actions or areas for improvement were identified which are included in the Recommendations in Chapter 11.

11 RECOMMENDATIONS

Based on a Phase 1 review, a number of preliminary recommendations are proposed. These will be further developed and added to in Phase 2, which also includes greater industry consultation to co-design improved regulatory approaches.

The preliminary recommendations are set out below.

11.1 Operational and Process Controls

The following recommendations are made to assist in improving odour management at composting facilities, based on the discussion within this report.

1. Turned windrow management – there is no best practice standard for the frequency and method of turning. Turning methods and schedules need to be optimised for the feedstock mix and site requirements. This requires a balancing of several factors such as maintaining aerobic conditions versus releasing accumulated odours; loosening of the compost and breaking up clumps versus reducing the porosity of the compost mix; and redistribution of moisture. The optimal turning strategy should be determined by an experienced operator through site trials and measurements.
2. That said, there are some common considerations in optimising turning the strategy:
    - Focus on adequate porosity - mix odorous materials with a generous and appropriate ratio of bulking material (e.g. shredded green waste) with particles that are not too small.
    - Minimise turning events for windrows containing odorous feedstocks, especially during the first 7-10 days of composting, with only the minimum turning required to support pasteurisation and moisture redistribution. This enables the odorous by-products generated during this initial phase to be oxidised to less odorous compounds before they are released to the atmosphere. The compounds will continue to decompose as they move through the windrow mass.
    - When turning with a front end loader, ensure that the operators do not drive up on the compost when windrows are being formed, which can cause compaction and reduce airflow.
3. Composters processing odorous materials in open windrows should be encouraged to experiment with caps of mature compost as a measure to reduce odour emissions during the initial stage of composting.
4. Composting operations that process highly odorous materials and/or are located close to sensitive receptors should consider and assess the implementation of some form of forced aeration and/or enclosed composting process, for at least the initial phase of composting.
5. Forced aeration strategies need to be optimised for a particular compost mix, so as not to have an adverse impact on odour emissions.
6. Engineered biofilters are a very efficient and cost effective method of treating odours if they can be captured from an enclosed or forced aeration composting system. They could similarly be applied to treat air from an enclosed feedstock receival and mixing building.
7. For best practice feedstock receival, operators should:
    - Keep an ample stockpile of bulking agent or high carbon material at the receiving area to immediately mix with all deliveries of odorous materials
    - Immediately mix potentially odorous materials upon receipt and ensure that materials are mixed uniformly throughout

- Consider enclosing the receival facilities for highly odorous materials and the initial mixing operation, with appropriate ventilation and biofilter systems
- Consider blanketing odorous solid materials with a thick layer of bulking agent
- Work with generators and collectors to increase collection frequency
- Have a system in place to assess and reject unacceptably odorous materials and eliminate troublesome feedstock sources
- Undertake small scale trials of new feedstocks prior to accepting regular full loads, to assess the practical aspects of handling the new material and to monitor its performance in a composting pile.

8. Operators should have a clear procedure in place to ensure the initial compost mix is optimal in terms of C:N ratio, moisture and porosity and to understand the odour potential of each feedstock. This should include testing and analysis of feedstocks to understand their physicochemical characteristics. Such testing need not be of every load for consistent feedstocks, but sufficient to understand the key parameters and variability.
9. Parameters such as temperature and pH should be regularly monitored throughout the composting process. Other parameters such as moisture content and oxygen levels may also be measured, particularly when processing wet or odorous feedstocks.
10. Compost piles should not be moved to the maturation or curing stage until the thermophilic stage of composting has been completed, indicated by consistent temperatures below 45°C (assuming all other aspects managed correctly).
11. Maturity tests such as SolvitaTM are widely accepted and can be done on site, to ensure compost is mature enough to be safely stored.

11.2 Regulation

Regulation of composting facilities is primarily controlled by conditions set out in the Environmental Authorities of each composting facility as well as general obligations which apply to all businesses in Queensland under the Environmental Protection Act 1994.

A review of those EAs has identified vast differences in the degree of control and regulation applied to each operator. In some cases, this is due to operators undertaking other environmentally relevant activities which increases the risk associated with the operation, such as processing of regulated wastes under ERA 55. In most cases though, it is a function of the age of each approval and the difficulty of changing an existing approval unless the operator voluntarily agrees to those changes.

The discrepancy means that there are some composters, including some very large-scale operations, which are operating with quite minimal controls over key environmental risk aspects such as waste acceptance, product quality, and management of odour, leachate and stormwater.

12. DES should investigate options to harmonise and reduce the inconsistency in EA conditions for composting operations with a similar risk profile and implement consistent minimum standards on key aspects such as waste acceptance (including testing requirements), product quality and odour control. There are good examples amongst some of the more recent existing EAs which may serve as a template, but the main focus should be on achieving consistency. The initial (and so far, limited) feedback from industry suggests they are open to changes provided it applies consistently to all and ‘levels the playing field’.

13. DES should consider whether there is a need for more stringent regulation or conditioning on sites that receive feedstocks considered to have a high or very high contribution to odour risk (as assessed in this report). This is not to suggest that these feedstocks are not suitable for composting, but that additional control measures may be warranted such as maximum blending ratios in green waste, additional requirements for their storage and mixing, more sophisticated processing, or additional analysis and documentation requirements.
14. With respect to odour, DES should consider whether the current outcomes-based approach is appropriate for regulating odours from composting facilities. Outcome based conditions are challenging to enforce when the outcome is difficult to measure and quantify or to trace back to a specific activity. Even more so when there are multiple operators potentially having a similar impact in one area, as is the case at Swanbank and elsewhere. Those existing conditions could be supplemented with additional conditions which address the root causes of odour as discussed in this report (e.g. feedstock storage and blending; windrow mixing and turning; maintaining aerobic conditions; and monitoring of key process parameters). There is a fine balance to be struck between being overly-prescriptive and maintaining flexibility for lower risk applications, which other states have not necessarily achieved in full. Therefore a Queensland specific approach is recommended, considering some of the operational methods noted in this report.
15. It is apparent that waste collectors and transporters exert a high degree of power within the organic waste management supply chain, yet it is the composters at the end of that chain that bear the brunt of regulation. In considering how to better regulate the composting industry, DES should be cognisant of this and consider options to better regulate the whole supply chain, making sure that waste generators and transporters are taking responsibility for providing adequate and accurate information about their waste streams, and ensuring they are managed appropriately. The new amendments under the Regulated Waste Framework will go some way to addressing this, provided they are properly applied by all parties in the supply chain and enforced by DES.
16. It is also apparent that the current waste tracking system is ineffective at tracking and flagging anomalous waste movements which may indicate waste has been taken to an inappropriate facility. DES should consider options to upgrade or overhaul the Waste Tracking System to an electronic platform that ensures that critical information is accessible to transporters, operators and the regulator in real time. This could potentially stop, for example, transporters 'shopping around' for a disposal option after being rejected from one facility.
17. For new facilities, industry could benefit from clear guidance produced by DES on the regulation of composting facilities including aspects such as locating composting facilities, separation distances, process and operational controls to minimise odour issues. Guidance documents from other states provide examples which may be considered, but the guidance should be tailored to Queensland context, be risk-based and allow a degree of flexibility for low risk applications.
18. To improve standards at existing facilities, industry seems open to development of minimum standards or a code of practice and generally lifting operational standards and knowledge levels. However, commercial competition means that such measures are unlikely to be developed by industry in isolation. Government may have a role to play in leading and facilitating the collaborative development of minimum standards and training requirements. Consideration would need to be given as to how to incentivise existing operators to comply with the standards.

11.3 Assessing odour from composting facilities

This report contains extensive information about different odour assessment and measurement techniques. It is apparent that some major composters in Queensland have rather limited technical understanding of how odours are caused and dispersed in the atmosphere, and it seems that the use of odour modelling as a tool to inform that understanding for their specific site is limited. As such, the project team recommends more robust assessment and analysis of odour sources and dispersion through modelling and sampling:

19. For any new proposed composting facilities, an odour impact assessment should be undertaken as part of the site's environmental and development approval processes. The assessment may vary depending on the risk posed by the scale, feedstocks and location but would generally include the following components:

    - An assessment of background odour in the existing environment. The assessment should include all sources of odour emissions from other existing activities in the local area with specific attention given to activities that may generate odours of a similar character or degree of offensiveness. This is to understand the current odour situation in the area, the frequency of potential odour episodes and the likelihood that the community is sensitised to odour or not. It is not for inclusion as background odour concentrations for use in an odour dispersion model unless the odour is deemed to be similar in character or from a sources at a similar activity, e.g., a proposed composting facility is located near an existing composting facility, landfill, waste transfer station, wastewater treatment plant or other activity where similar volatile sulfur and organic compounds may be released.
    - A representative odour dispersion model should be developed to assess the odour footprint of facility operations under all site-specific operating and meteorological conditions. The meteorological model's performance should be evaluated against observed data or be developed from observations collected by an automatic weather station set up in accordance with the Australian standard AS3580.14 (2014). The model should adequately represent the important features of the region's topography, land surface characteristics, and sensitive receptor locations and density.

20. For higher risk facilities, once it is approved and commences operation, an odour emissions audit should be conducted to develop a representative odour emissions inventory of the site's operations. A representative number of samples from each emission source should be collected and analysed by the methods prescribed in the Australian standards e.g., AS4323.3 and AS4323.4, to suitably assess the site's odour footprint. Further details of odour sampling, testing and assessment techniques are provided in the EPAQ (1997) and EPA (2006). Notwithstanding the guidance provided in these standards, consideration should be given in sampling device selection to the conditions, chemical mass transfer properties and diffusion mechanisms taking place at the surface of each odour source being sampled to ensure worst case emissions are captured for analysis.

    Once operational data is collected, it can be fed back into the site odour dispersion model (developed for the facility's environmental approvals) to calibrate and refine the model. The odour impact assessment can then be reviewed to evaluate whether the facility is likely to comply with the conditions under which it was approved, or whether further control measures may be warranted to ensure ongoing compliance. The calibrated dispersion model will then be a valuable tool for the operator to understand how their operation can impact on sensitive receptors under different conditions.

    The performance of the odour dispersion model generated for the actual operating conditions could be evaluated and verified through a series of field ambient odour assessments. A minimum of ten field odour surveys in a period of 30 days should be conducted at different times of the day and in different meteorological conditions. This assessment could be repeated at least once during a different season within the first year of operation. Selection of seasons should be informed by dispersion model results and consider the following:

- Times of the year when winds are most likely to blow emissions towards key identified sensitive receptor areas,
- Peak odour emissions (e.g. potentially summer time) when ambient and compost temperatures are likely to be at their maximum, thereby generating peak odour emissions. This may also coincide with the period when compost material volumes are at their peak.
- Worst case dispersion conditions (e.g. winter time), particularly at night and around sunrise and sunset, but not limited to these times, and elevated ground-level odour concentrations.

An odour impact assessment technical report of these studies should be prepared by a suitably qualified and experienced person. There may be exceptions granted to this process for facilities are demonstrably at low risk of impacting on sensitive receptors.

21. For an existing composting facility that has been the subject of a certain number of complaints (to be determined by the regulator) from the community related to offensive odours that may cause nuisance, the proponent of the facility should be required to conduct an odour impact assessment of its operations. The assessment should include, but not be limited to:

    - An odour emissions audit, with sampling and measurement by the methods prescribed in the Australian standards e.g., AS4323.3 and AS4323.4. The results of the audit should be compiled into an emissions inventory for comparison with the inventory developed after the facility's approval.
    - The prediction of odour concentrations, at and beyond the boundary and at sensitive receptor locations, associated with the new inventory (see item 14 above) by odour dispersion modelling. The odour dispersion model developed for the site's approval may be used for this purpose, however, depending on the time elapse between the initial site approval and the existing odour issue, there may be many reasons for the original model to be unsuitable for use, including the availability of the model, the type of model used, and advancements in models and modelling techniques. Changes in regional meteorology should also be considered. The odour impact assessment report must at least consider the likely incremental increases relating to the following:
        a. all phases of processing (e.g. pre-treatment, decomposition, aeration and maturation),
        b. raw organics and organic products managed at the premises, including impacts during receipt and storage (i.e. including stockpiling of organics),
        c. movement of raw organics and organic products at and to/from the premises,
        d. management of biogas at the premises (e.g. biogas flaring), where closed system composting is conducted, and biogas is collected.
    - Field ambient odour surveys should be conducted to evaluate odour model performance and provide an actual assessment of odour experienced in the surrounding area.
    - Consideration may also be given to ongoing and routine field ambient odour assessment surveys as an odour management tool. Surveys should be conducted by suitably trained and qualified odour assessors, and preferably independent of the occupier's organisation. Should staff from the occupier's organisation conduct these surveys, they should not be plant operators that spend their time on the site and are desensitised to the odours released. These surveys should be recorded and documented appropriately in order for the regulator to assess compliance upon request.

22. For all facilities, operators should undertake an odour audit or odour balance study can be a useful exercise to identify and quantify odour emissions from each stage of the process, resulting in an odour emissions inventory for the site. This will vary for each site but it is worth noting the receival area and curing piles can be major odour sources, in addition to the mixing and composting stages.

23. Ongoing environmental management of existing and future composting facilities should include, but not be limited to:

    - A site-specific odour management plan, the purpose of which is to identify odour sources and proactively reduce the potential for odour generation as well as to have a reactive plan for managing odour during upset conditions. An odour management plan may include the following:

        e. An inventory of all sources of odour,

        f. Odour sources and controls under normal conditions,

        g. Odour monitoring and recording regime,

        h. Odour management during upset conditions, and

        i. Routine maintenance of odour control equipment (where installed).

    - Site-specific meteorological data should be collected and recorded in accordance with the Australian standard AS3580.14 (2014) and EPA NSW (2016). The establishment of meteorological stations at all higher risk composting and related organics processing facilities should be encouraged to help verify odour complaints and evaluate or enhance dispersion model performance. The meteorological monitoring station should be maintained in good working order. Meteorological stations installed at composting and related organics processing facilities should, where practicable, continuously measure and electronically log the following parameters, at a minimum, in accordance with the Australian standard AS3580.14 (2014):

        a. Wind speed at 10 metres (m/s),

        b. Wind direction at 10 metres (°),

        c. Ambient temperature at two levels (2 metres and 10 metres) (°C),

        d. Parameters needed to determine the Pasquill-Gifford stability class—that is, either sigma theta (°) or solar radiation (W/m2).

    - All complaints reported to the occupier regarding odour must be considered in the light of meteorological data and/or site activities such as delivery of unusual organics to identify any correlations.

11.4 Swanbank Composting Improvements

Based on the review of the two Swanbank composting facilities, a number of common actions or areas for improvement were identified which are in line with industry best practice and could potentially be applied more broadly:

24. Operators receiving odorous liquid and other materials in sensitive areas should consider enclosing the reception and storage facilities for those feedstocks as well as the feedstock mixing areas, within an airtight structure along with air extraction to a biofilter.
25. Operators should implement operational procedures to avoid or minimise the formation of leachate through appropriate solid and liquid blending ratios and efficient methods of mixing the materials.
26. Where leachate is generated and storage is unavoidable, it should be able to drain freely from all operational areas and stored in an aerated pond to maintain aerobic conditions, or in enclosed tanks with adequate ventilation systems. Leachate storages should have adequate capacity to avoid uncontrolled overflows in heavy rainfall and be regularly desilted to prevent excessive accumulation of organic solids, which leads to anaerobic and odorous conditions.
27. Operators using open windrows should consider simple methods of mitigating odour from windrows in the early stages of composting, such as application of a thick layer or blanket of mature compost (unscreened or oversize fraction) and/or pure green waste mulch over the windrows once they are initially formed.
28. Large scale and higher risk composting facilities should be encouraged to develop an odour dispersion model, together with on-ground sampling to calibrate the modelling, to better understand the impact of different point and fugitive odour sources and activities, and the effects of different weather conditions.
29. Operators should provide training of staff to understand odour causes, dispersion and best practice control methods. DES can potentially support by developing technical guidance materials and manuals.

A number of recommendations have also been made separately in that report around the way that DES regulates and engages with the Swanbank composters.

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APPENDIX A

Review of International Odour Regulations

The project team has reviewed odour regulations and impact assessment criteria in various countries and jurisdictions around the world. The review focused on odour measurement techniques, the assessment of impact and nuisance including methods such as dispersion modelling and their related odour impact criteria, legislative instruments, odour management and control measures. Detailed summaries of the regulations in each jurisdiction are provided below.

The jurisdictions have been selected to illustrate the broad spectrum of odour assessment and regulatory techniques, including odour impact criteria, used around the world, and specifically, in relation to the assessment of odour from composting and other waste management related activities. Where available, odour impact criteria for composting activities are compared with criteria for other industrial and agricultural activities to illustrate the difference and provide the background to the different criteria approach.

The overview of international regulations below is largely based on analysis by Brancher *et al* 2017 and other sources as noted.

11.4.1 Europe

Western Europe has been a leader in odour science and the development of measurement techniques and regulations for nearly five decades. Key countries that have been highly active in this field include The Netherlands and Germany. In more recent times, the United Kingdom, Italy, Spain, Belgium and France among a few others have developed regulations and European researchers have contributed substantially to the scientific literature on the subject. This has also included the assessment, control and management of odours from organic waste composting activities.

The European Commission, under the Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control), has published a series of Best Available Technique (BAT) reference documents, known as the BREFs, including a volume on Waste Treatment (Pinasseau *et al*, 2018). This document includes BAT for air and odour emissions control and management from waste treatment, as well as BAT for organic waste compost processing.

11.4.1.1 Germany

The regulatory framework on air quality in Germany has been adopted from European Union provisions and promulgated under The Act on the Prevention of Harmful Effects on the Environment Caused by Air Pollution, Noise, Vibration and Similar Phenomena, referred to in short as the Federal Immission Control Act (BImSchG - Bundes Immissionsschutz Gesetz) and its subordinate administrative regulations and ordinances. The Technical Instructions on Air Quality Control (TA-Luft, 2002) provide guidelines for authorities to manage air pollution, including odour. However, TA-Luft does not set out odour impact criteria, this is observed within the national odour regulation called Guideline on Odour in Ambient Air (GOAA, 2008)

Elements of the German standard approaches to odour measurement and assessment, in particular the sampling of odours, the measurement of odour intensity and hedonic tone, and the measurement and assessment of odour in ambient air by field inspection, have been adopted selectively and to varying degrees in Australia and other jurisdictions. However, the comprehensive German approach to odour assessment is fairly unique and differs markedly from most jurisdictions. GOAA (2008) addresses odours from industrial and livestock facilities only, and neglects odours from road traffic, domestic heating, vegetation, manure spreading, and other similar sources. Assessment criteria are based on measurement and assessment of recognizable odour from existing sources and the ‘odour-hour’ concept. Odours in ambient air may be recorded only if they can be identified during measurement in the field or in odour exposure prognoses by means of dispersion models. The concept of an odour-hour is applied in the guideline VDI 3940 - Part 1:2006 (VDI, 2006), where "one odour-hour means one positively assessed single measurement. A single measurement has a positive result if the fraction of time during which an odour was unambiguously identified comes up to or exceeds a predefined percentage value. This definition was derived from the general properties of the sense of smell, in particular its pronounced ability to adapt to stimuli. It is assumed that, although the summarised duration of all odour episodes is identical, many short excesses of the odour threshold in one measurement interval have a higher effect on odour annoyance than only a few continuous stimuli with a shortened effect due to adaptation. Consequently, the concept of odour-hours weights many short odour episodes more heavily than fewer long ones".

The assessment criteria are based on exposure limit values in ambient air. As a rule, the odour exposure is classified as a severe nuisance if the total odour exposure (EXP_{tot}) exceeds the regulatory exposure limit value (EXP_{lim}) set as follows:

- Residential and mixed areas: 0.25 ou_E/m^3 at the 90th percentile;
- Commercial, industrial, agricultural areas: 0.25 ou_E/m^3 at the 85th percentile.

These limit values are relative frequencies of odour-hours. Short-time peak concentration observations of 1-second are converted to hourly mean values using a constant peak-to-mean value (*F*) of 4. A concentration threshold of 1 ou_E/m^3 is used, therefore, applying *F*, a C_t = 0.25 ou_E/m^3 for 1-hour average mean concentration is given. The EXP_{tot} is calculated, in this manner:

$$EXP_{tot} = EXP_{exist} + EXP_{add}$$

where, EXP_{exist} is the characteristic value of the existing odour exposure, and EXP_{add} is the expected additional odour exposure. "The existing exposure is the odour exposure originating from the existing installation without the expected additional exposure caused by the development to be licensed. The characteristic value EXP_{exist} is computed for every assessment square of the area under investigation from the results of the grid measurements or dispersion calculation".

Furthermore, the guideline introduces the concept of a nuisance relevant characteristic value $EXP_{tot,nr}$ to exposure limits for livestock odours on agricultural land. This is a weighing factor (f) for individual types of animals, related to their offensiveness, e.g. poultry f = 1.5, fattening pigs f = 0.75 and dairy cows and young cattle f = 0.5. The odour frequency of animals not listed will appear without weighting factor in the calculation of f_{tot}. The hedonic tone of different odours can be weighted according to the method of polarity profiles in to VDI 3940 - Part 4:2010 (VDI, 2010b). Consequently, the benchmark exposure limit is reduced for unpleasant odours and increased for pleasant odours.

Compliance with the odour criteria is attained where the total odour exposure (characteristic value of the expected additional odour exposure) does not exceed 0.25 ou_E/m^3, at the 98th percentile. At this level, it is assumed that the activity will not significantly increase the odour annoyance effect above the existing odour exposure. "This is called the criterion of irrelevance: the insignificance of the expected additional odour exposure".

11.4.1.2 The Netherlands

The Netherlands has a long history of regulating environmental odours that stretched back the 1970s. The first sector to be regulated on a national level to managed odour impacts was the intensive livestock rearing industry, and in particular, the country's very large pig production industry. The first practical guideline introduced in 1971 set minimum separation distances between residential areas and livestock handling facilities. A more substantial quantitative air quality guideline for odours from industrial sources was introduced in 1984 that included the measurement of emissions by olfactometry and dispersion modelling to assess the frequency of exposure to odour concentrations above a certain limit in ambient air over hourly averages. A national framework (Netherlands Emission Guidelines [Nederlandse Emissie Richtlijn, NeR]) to assess and manage odours was introduced in 1995, until then odour permitting had been regulated at the state level (Van Harreveld, 2003). The general policy was to prevent and, if not possible, to limit as much as possible nuisance odour. However, in 2016 the NeR was withdrawn.

While having no real legal status, the NeR was a national guideline with the objective of harmonising environmental permitting in The Netherlands concerning the reduction of air emissions. The guideline provided emission factors and exposure criteria (maximum impact standards) for specific odour-emitting activities according to the offensiveness of the odour. Therefore, limits were source-specific with more stringent criteria applied to sources with more offensive odours. Odour concentration threshold varied from 0.5 ou_E/m^3 to 25 ou_E/m^3 and the percentiles from 98th to 99.99th. Model predicted odour concentrations were based on hourly averages rather than peak concentrations using a peak-to-mean concept. Discontinuous sources (i.e. emissions during a limited number of hours per year) were not only tested against the baseline 98^{th} percentile (suitable for evaluating continuous sources) but also with higher percentiles.

Industrial activities regulated with odour emission criteria included grass dryers, livestock feed industry, bakeries and pastry, slaughterhouses, meat processing, cocoa beans processing industry, coffee roasters, breweries, asphalt mixing plants, composting of green waste and composting of organic waste. The Dutch odour impact criteria for composting, set over hourly averages on an annual basis, is as follows:

- Composting of green waste:
  - 1.5 ou_E/m^3 at the 98th percentile for new and existing facilities;
  - 3 ou_E/m^3 at the 99.5th percentile and 6 ou_E/m^3 at the 99.9th percentile is also normative;
  - Only applicable for plants with production capacity exceeding 20,000 tonnes/year;
- Composting of organic waste:
  - 1.5 ou_E/m^3 for new facilities or 3 ou_E/m^3 for existing facilities, 98th percentile; odour-sensitive locations.

The odour criteria are industry specific and have flexibility for regulators to make decisions based on varying assessment conditions. The criteria also consider odour impact caused by existing industries, presumedly in reverse amenity situations, where sensitive land uses encroach upon established industrial areas, different to new facilities by assessing existing industries against less stringent criteria. The range of percentile statistics used is also a lot broader than the statistics applied in Australia.

Odour assessment criteria do vary in some Dutch jurisdictions. A notable example is in the area of North Brabant, where odour emission rates are adjusted according to the odour's hedonic tone before modelling and predicting ground-level odour concentrations. Calculations are based on a "hedonic weighted ou_E per unit of time", expressed in $ou_E(H)/h$. For instance, if a source has an odour emission rate of 630 Mou_E/h and an odour concentration of 7 ou_E/m at H = -1, then the hedonic weighted odour emission rate is 90 $Mou_E(H)/h$ (as a result of 630 Mou_E/h / 7 ouE/m^3).

Therefore, dispersion modelling results are expressed as $ou_E(H)/m^3$ and compared against the criteria set for North Brabant. The assessment framework includes guideline values and upper limit values on the basis of 98th percentiles and 99.99th percentiles for new and existing activities located in residential, mixed and other areas. The concentration thresholds vary from 0.5 to 100 $ou_E(H)/m^3$.

Since the NeR was withdrawn, the European environmental directives have been implemented in the Environmental Management Act (Wet Milieubeheer) and the Environmental Activities Decree (Activiteitenbesluit milieubeheer). As before, the general principle of the Dutch odour policy is to minimise odour pollution and prevent new pollution. This principle, together with the use of the Best Available Techniques (BAT), is the heart of the odour policy in The Netherlands. Additionally, regional and local authorities can perform adjustments in the standards to consider relevant (local) interests, in order to reach an acceptable odour condition that meets the relevant environmental values.

11.4.1.3 Belgium

In Belgium, odour is regulated at the regional level (similar to our states). In the Walloon Region, industrial activities are divided into three classes according to the importance of their impact, with Class 1 activities being potentially the most polluting. Each facility can be associated with one or more classes based on the activity operating within the facility. Composting facilities are called out for special mention, requiring odour dispersion modelling studies for their assessment. The odour impact criteria for composting facilities with a quantity of material stored greater than or equal to 500 m^3, that should not be exceeded at the property line of the nearest dwellings, is:

- 3 ou_E/m^3 at the 98^{th} percentile, 1-hour averaging period (*F* 1.0).

There is no comprehensive legal framework of odour regulation in Flanders, with odour policy scattered in various laws, decrees and regulations, and municipalities also having the authority to establish local policies. Notwithstanding this, field inspections were developed in the Flemish region for estimating the total emission rate of odour-emitting sources. This method combines odour patrols, which determine the spatial extent of the perceivable odour plume downwind of the source, with reverse dispersion modelling. The sniffing method is standardised in a code of good practice (Bilsen et al, 2008).

In a similar manner to the European EN16841 Part 2 method, field survey measurements are expressed as sniffing units per cubic meter (su/m^3, or se/m^3 from *snuffeleenheden*), which represents the minimum amount of the odorant, present in 1 m^3 of air, with the capacity to generate an identification response to some odour experienced by a panel member in the field conditions. The concept of sniffing units is similar to odour units, however measured in the field rather than in the laboratory.

The method aims to determine the maximum distance, both longitudinally and laterally, of the odour plume from an activity detectable by odour assessors. Meteorological conditions measured at the time of the odour observations are used in a Gaussian dispersion model to predict a short-term impact with a similar plume footprint. The odour emission rate required to estimate this plume footprint is then 'back-calculated'. Once the odour emission rate is determined, the model is run for a minimum of one year at that rate to generate odour concentration isopleth maps (in units of su/m^3 or se/m^3). The method now provides the basis for the EN16841 standard (2016), *Ambient Air – Determination of odour in ambient air by using field inspection, Part 2: Plume Method*.

The modelling-based odour impact criteria is then adapted to the odour emission's nuisance level based on the following hedonic tone classifications at the 98^{th} percentile statistic:

- very unpleasant: 0.5 se/m^3;
- unpleasant: 1.0 - 1.5 se/m^3;
- neutral: 2.0 se/m^3;
- pleasant: 2.5 - 3.0 se/m^3;
- very pleasant: 3.5 - 5.0 se/m^3.

Some of the criteria were derived on the basis of dose response relationships, and others were based on the type of odour offensiveness of the facility (Van Broeck and Van Elst, 2003; VITO, 2012 as cited in Brancher *et al* 2017), for example:

- Textile finishing plants, biofilters, WWTP aeration basin, c*omposting installations of green or kitchen and garden waste*: 1.5 se/m^3;
- Vegetable oil extraction and processing, *composting plant for mushroom substrate*: 1 se/m^3;

Therefore, the realisation of the assessment framework in highly sensitive receptors for very unpleasant smells is conducted in this fashion:

- < 0.5 se/m^3: negligible impact;
- 0.5 - 2 se/m^3: moderate negative impact;
- 2 se/m^3: strong negative impact.

A limit of 10 se/m^3 at the 98th percentile is considered to be the maximum level at which unacceptable nuisance can always be expected. The following assessment framework is set for the consideration of the odour sensitivity of the receptor for very unpleasant odours:

- Target values
  - 0.5 se/m^3 for highly sensitive receptors;
  - 2 se/m^3 for moderate sensitive receptors;
  - 3 se/m^3 for low sensitive receptors.
- Limit values
  - 2 se/m^3 for highly sensitive receptors;
  - 5 se/m^3 for moderate sensitive receptors;
  - 10 se/m^3 for low sensitive receptors.

For more neutral odours (e.g. biofilter) the assessment framework is as follows:

- Target values:
  - 1.5 se/m^3 for highly sensitive receptors;
  - 3 se/m^3 for moderate sensitive receptors;
  - 5 se/m^3 for low sensitive receptors.
- Limit values:
  - 3 se/m^3 for highly sensitive receptors;
  - 5 se/m^3 for moderate sensitive receptors;
  - 10 se/m^3 for low sensitive receptors.

11.4.1.4 United Kingdom

In the United Kingdom, odours are currently managed under the following legislative framework:

- Environmental Protection Act (EPA),
- Town & Country Planning Act (TCPA),
- Environmental Permitting regulations (EP) (England & Wales), and the
- Pollution Prevention and Control regulations and Waste Management Licensing regulations (PPC & WML) (Scotland and Northern Ireland).

Waste management activities are regulated under the EPA, along with industry, agriculture and wastewater treatment assets. Assessment criteria for ambient odour are provided in the Integrated Pollution Prevention and Control directive (IPPC), set out in Appendix 3 (modelling odour exposure) of the H4 Odour Management (EA, 2011). The criteria limits are designated by offensiveness, as follows:

- 1.5 ou_E/m^3 at the 98th percentile, 1-hour averaging period (F 1.0), for odour emission sources as processes involving decaying animal or fish remains, processes involving septic effluent or sludge, biological landfill;
- 3 ou_E/m^3 at the 98th percentile, 1-hour averaging period (F 1.0), for intensive livestock rearing, fat frying (food processing), sugar beet processing, well aerated green waste composting;
- 6 ou_E/m^3 at the 98th percentile, 1-hour averaging period (F 1.0), for brewery, confectionery, coffee.

Local factors may influence the criteria limits, as for instance, if the local population has become sensitised by a source of nuisance odour, the limit may be reduced by 0.5 ou_E/m^3.

Application of Best Available Techniques (BAT) as control measures is a prerequisite for all industries, where applicable. Under the European IPPC legislation (Directive 2008/1/EC) and Industrial Emissions Directive (IED 2010/75/EU), BATs are defined to reduce overall environmental impacts on an industry-by-industry basis. To demonstrate the efficacy of the BAT measures and to test uncertainties, dispersion models are run for different design and “what if” scenarios using hourly meteorological data for a period of at least three, preferably five years.

11.4.1.5 Spain

Odour is regulated in Spain at local government levels through municipal ordinances or activity licenses rather than by a federal regulatory instrument.

In Catalonia, the Department of Environment and Housing produced in 2005, a draft of a Law against odorous pollution (Generalitat de Cataluna, 2005). This draft law has been developed over the years with the objective of introducing it across the Spanish territory. However, to date, nothing consolidated has been established.

According to the Draft, for existing activities the emissions associated with odour-generating sources are measured using the European olfactometry standard EN 13725:2004. For new activities, the estimation of the emission rate is obtained by applying emission factors. Objective target values of odour emission are applied in residential areas, as follows:

- 3 ou_E/m^3 for waste management, rendering of animal by-products, distillation of animal and vegetal products, slaughterhouses, paper and pulp industry;
- 5 ou_E/m^3 for livestock, processed meat, smoked food, rendering of vegetal by-products, treatment of organic products, wastewater treatment plants;
- 7 ouE/m^3 for roasting and processing coffee or cocoa facilities, bread ovens, pastry and cookies, beer, production of flavours and fragrances, drying plant products.

Therefore, the odour limits are designated by offensiveness. The less offensive the odour is, then the higher the tolerable level of its concentration. Dispersion model predictions are assessed at the 98th percentile of hourly mean concentrations during a year (F = 1). Emissions are considered odorous if the concentration in ambient air is greater than 10 ou_E/m^3, which leads to nuisances, or if compliance with the target criteria is not met.

11.4.1.6 France

In France, air quality is primarily regulated by European Directive 2008/50/EC and other French national legislation. Of these, Law No. 76-663 of 19 July 1976 is related to classified facilities for environmental protection and is part of the Environmental

Code, forming the basis of the requirements of odour pollution included in the Ministerial Decree of 2 February 1998 and sectorial decrees (MEDDE, 2016a). Specific guidance with maximum odour impact criteria for composting facilities is set within the Decree of April 22 April of 2008 (last updated by Decree of 27 July of 2012) and sets the technical requirements to be met by composting plants subject to authorisation (JORF, 2008).

Article 26 of the decree indicates that:

- For new and existing installations, the odour concentration calculated by a dispersion model at the level of human occupation zones listed in Article 3 within 3 km of fence line of the installation should not exceed the limit of 5 ouE/m^3 more than 175 hours per year (i.e. 98th percentile), 1-hour averaging period (F 1.0).

Appropriately situated composting facilities in a low sensitivity zone with adequate separation distance to sensitive receptors, or facilities with an overall emission rate that does not exceed 20 x 106 ouE/h, do not require a dispersion modelling study.

11.4.2 The Americas

The development of odour regulations has come a little later in the Americas when compared to Europe and Australia.

11.4.2.1 Canada

In Canada, odour is not regulated federally and is generally regulated in some provinces according to the principles of Nuisance Law, rather than by specific odour impact criteria. Odour sampling at the source and testing is conducted in accordance with EN 13725:2003 and ASTM E679-04, with odour dispersion modelling performed to assess ground level odour concentrations against an odour assessment criterion. Notable odour regulations in Canada include:

- Alberta: Guide of good practices related to odour management in Alberta (Clean Air Strategic Alliance, 2015),
- Quebec: Clean Air Regulation, 2011, Environment Quality Act, Quebec,
- Montreal: Reglement No. 90 (1986), with impact assessment criteria set out in CUM (2001),
- Boucherville: Reglement Numero 2008-109,
- Manitoba: The Manitoba Conservation Environment Act, 2005 (Manitoba 2005),
- Ontario: Environmental Protection Act 1990, Section 6, with specific odorous compounds being regulated under Ontario's Ambient Air Criteria Regulation 419/05 (2012).

In Quebec, guidelines promulgated by the Minister of Sustainable Development and Parks for specific sectors including composting (MDDEP, 2012) and biogas activities (MDDEP, 2011) established the following multi-percentile odour impact criteria in ambient air:

- 1 ou_E/m^3 at the 98th percentile, 4-minute averaging period (F = 1.9),
- 5 ou_E/m^3 at the 99.5th percentile, 4-minute averaging period (F = 1.9) and applied concurrently at the nearest off-site sensitive receptor.

Despite the results of the odour dispersion modelling assessment, a minimum separation distance of 500 m from any residential, commercial or public places is applied to any new composting site with volumes of material less than or equal to 7,500 m^3. For a developer that does not conduct a dispersion modelling study, the separation distance will be increased to 1 km. For composting sites processing more than 7,500 m^3 of material, a separation distance of 1 km from sensitive land uses is applied regardless of the results of the odour dispersion modelling assessment. The distance may be reduced to 500 m if certain operating practices are followed (MDDEP, 2012).

For biogas activities, a separation distance of 1 km is applied when the facility is situated in residential, commercial or public areas, despite the results of the dispersion modelling assessment. The buffer can be reduced to 500 m if certain operating practices are followed (MDDEP, 2011).

In Montreal, Reglement No. 90 (1986) was promulgated to manage air quality in the Montreal Urban Community (CUM) with the following odour impact assessment criteria set out in CUM (2001):

- 1 ou, not to be exceeded outside the facility's fence line, and
- Dispersion simulation is conducted using a simplified Gaussian calculation defined in *Equation 3.04*, of the by-law.

In Boucherville, Reglement Numero 2008-109, was promulgated to control odour emission (Boucherville, 2008), and as such, Article 4 states the following odour impact criteria:

- 10 ou/m^3 at the 100th percentile, 4-minute averaging period (F = 1.9),
- 5 ou/m^3 at the 98th percentile, 4-minute averaging period (F = 1.9),
- AERMOD is the regulatory air quality model,
- Odour impacts are calculated 1.5 m above the ground at the fence line or at the limits of industrial areas, if the facility is located within an industrial area,
- In case of significant deviation or frequently exceeding the criteria set in Article 4, authorities may require the implementation of an electronic nose system to continuously monitor emission sources to provide real time odour data.

In Manitoba, the Manitoba Conservation Environment Act, 2005 (Manitoba, 2005) was promulgated by Manitoba Conservation, and contains the following strategies for odour management and assessment criteria:

- 2 ou, for residential areas,
- 7 ou, for industrial zones,
- The maximum desirable level is an odour concentration of less than 1 ou,
- Odour measurements are specified to be measured in two tests conducted between 15 and 60 minutes apart, which suggests field evaluations are performed. However, measurements cannot be conducted on the impact of odour from proposed developments that do not exist, and consequently, a predictive dispersion modelling approach is taken,
- For new or expanded facilities, at least one of two levels of odour dispersion modelling should be conducted such as a screening level (Screen3) and/or a refined modelling approach (AERMOD, ISC3, ISC-PRIME, CALPUFF).

In Ontario, odours are regulated under the Environmental Protection Act 1990, Section 6, where odour is a prohibited contaminant. Ambient concentrations of specific odorous compounds are regulated under Ontario's Ambient Air Criteria Regulation 419/05 (2012). Dispersion modelling procedures are also set out in this regulation. No odour criterion is promulgated in the regulations, however the following criterion is commonly applied at sensitive receptor areas for planning approvals, environmental evaluations in response to odour complaints, and installed as a condition of approval in air permits (Ferguson and Tebbutt (2015), as cited in Brancher *et al* 2017):

- 1 ou at the 99.5th percentile, 10-minute averaging period (F = 1.65),

- Compliance is demonstrated by source emissions measurement and dispersion modelling, and
- Minimum separation distances for sewage treatment facilities, agricultural and industrial facilities have also been established.

11.4.2.2 United States

In the USA, odours are not regulated federally under the Clean Air Act or addressed in the National Ambient Air Quality Standards (NAAQS). In 42 of 50 states, odour is regulated by the principles of Nuisance Law, while some states provide odour regulations that set out ambient odour dilutions-to-threshold (D/T) limits. The D/T evaluations are made by human assessors using a field olfactometer such as a Scentometer, the St Croix Sensory Nasal Ranger or the Scentroid SM100. In summary:

- 10 states regulate according to dilution to threshold (D/T) limits including Colorado (Regulation No. 2), Connecticut (Regulation 22a-174-23), Delaware (Air Regulation Number 1119), Illinois (Title 35, Subtitle B, Chapter 1, Part 245), Kentucky (Regulation 401KAR53:010), Missouri (Title 10, Chapter 6, Section 165), Nevada (NAC 445B.22087), North Dakota (Chapter 33-15-16), West Virginia (Title 45, Series 4), and Wyoming (Chapter 2, Section 11).
- Other states vaguely mention odours with the use of field olfactometry or D/T method including Massachusetts, North Carolina, Oregon, Pennsylvania, and Washington.
- Local governments also stipulate odour regulations, e.g., Oakland, San Diego, Seattle, Allegheny County.
- Field olfactometry is the most employed technique to assess odour pollution levels within the US.
- Separation distances are also used in some jurisdictions for livestock activities including Illinois, Iowa, Kansas, Missouri, North Carolina, Oklahoma, South Carolina, South Dakota, Wyoming.
- Odorous air samples are measured using the American Standard ASTM E679-04. Odour laboratories also operating in accordance with the European standard EN 13725:2003 triangular forced-choice method, also meet the requirements of ASTM E679-04.

11.4.3 Asia

11.4.3.1 Japan

Odour is regulated in Japan on a national level under the Offensive Odour Control Law (Law No. 91 of 1971 – Latest Amendment by Law 71 of 1995). The regulation prescribes two different mechanisms of odour control:

- Concentration of offensive odour substances, or
- Odour index.

Based on either of these two mechanisms, regulators can set any of the following three standards corresponding to odour emission source type from facilities (Brancher *et al* 2017):

- Regulation standard on the fence line;
- Regulation standard for stack emissions;
- Regulation standard for liquid effluent outlets.

The regulation standards are set according to geographical and demographical conditions with all kinds of facilities within regulated areas controlled by the law. The regulation applies regardless of the type, scale or management organisation of a business. Densely populated areas and suburbs with schools and hospitals are the typical areas regulated (Brancher *et al* 2017).

For the concentration of offensive odour substances, the regulation sets out the maximum concentration permitted for 22 individual odorous compounds. These limits apply at ground level at the fence line of the facility being regulated.

The Odour Index approach is a quantitative method to determine the intensity of odours. It can be calculated by multiplying the common logarithm of the dilution rate by the factor 10 (Odour Index = 10 x Log [odour concentration]), where the odour concentration is measured using the Japanese triangular odour bag method. Measurements are based on the dilution ratio until the odour cannot be detected any longer using human olfaction. The intensity scale used varies from 0 (no odour) to 5 (very strong) and this criterion is based on the premise that an Odour Index associated with an odour intensity scale ranging from 2.5 to 3.5 (equivalent to 10-21 Odour Index) is deemed acceptable at the site boundary (Iwasaki, 2003; MOE, 2003b, a; Kamigawara, 2003; cited in Brancher *et al* 2017).

11.4.3.2 China

In China, air quality is legislated under various standards, including (Brancher *et al* 2017):

- Ambient air quality - under the national ambient air quality standards (GB 3095-2012) that are released by the Ministry of Environmental Protection (MEP),
- Air pollutant emissions – under the Integrated Emission Standard of Air Pollutants (GB 16297-1996), which is promulgated under the Law on the Prevention and Control of Air Pollution and sets emission limits for 33 air pollutants and various requirements for the implementation of the standard,
- Odour - Emission Standard for Odour Pollutants (GB 14554-93), that specifies emission standards according to stack height for eight odorous pollutants including ammonia, trimethylamine, hydrogen sulfide, methyl mercaptan, dimethyl sulfide, dimethyl disulfide, carbon disulfide, styrene, and odour (i.e. the role of chemical compounds within a mixture). In addition to this, maximum concentration limits in ambient air at the facility boundary are set for these eight odorous pollutants and odour.

The odour standard is applicable to the environmental management of any facility emitting odorous gases. It is applicable to existing, expanding and future facilities and includes varying criteria for different land uses (termed as class 1, 2 or 3) (MEP, 2016, cited in Brancher *et al* 2017). Class 1 standards apply to special protection regions such as national parks and historic sites. Class 2 standards apply to residential and mixed areas and Class 3 to special industrial areas.

If the emission source height is greater than 15 m, then the emission standards apply. Alternatively, if the source height is less than 15 m, the emission limits (i.e. limit at the receptor) are considered, as follows (Brancher *et al* 2017):

- Class 1: 10;
- Class 2: 20 for new, modified and 30 for existing facilities;
- Class 3: 60 for new, modified and 70 for existing facilities.

The unit for odour concentration, in the GB 14554-93 Standard (MEP, 2016), is described as dimensionless, although the Japanese triangular odour bag method is applied to measure odour con- centration (GB/T14675-93) and the flow rate is calculated in m^3/h. Additional methods are described for the determination of the concentration of the eight odorous pollutants. (Brancher *et al* 2017)

For continuous emission sources, the sampling frequency is a minimum of four samples collected at a minimum interval of two hours in order to obtain the maximum value measured. For intermittent sources, the highest odour emission rate is selected of three samples measured. For emission limits, odour criteria are set according to the stack height and maximum emission rate, respectively (Brancher *et al* 2017):

- 15 m: 2000;
- 25 m: 6000;
- 35 m: 15,000;
- 40 m: 20,000;
- 50 m: 40,000;
- ≥ 60 m: 60,000.

11.4.3.3 South Korea

Odour is regulated in South Korea under the Malodor Prevention Law (KMOE, 2008, cited in Brancher *et al* 2017). This law recommends that the air dilution sensory (ADS) test, adapted from the Japanese triangular odour bag method, is used as a primary means to assess the level of odour pollution in dilution-to-threshold (D/T) ratios (Kim, 2016, cited in Brancher *et al* 2017). Air samples are collected from odour sources (emission limits) or other surrounding areas (emission limits), as follows (Park, 2004):

- Maximum emission standard (outlets including stack):
  - Facilities in industrial areas: 1000 D/T;
  - Facilities in other areas: 500 D/T.
- Maximum impact standard (boundaries of facilities including enclosures):
  - Facilities in industrial areas: 20 D/T;
  - Facilities in other areas: 15 D/T.

In addition to the assessment of odorous mixtures, odour relevant concentration criteria are provided for 22 individual odorous compounds (Kim and Kim, 2014). Measurements are made and assessed for these chemical compounds at critical off-site locations and at emission points.

11.4.4 Summary of Australian and International Odour Impact Assessment Criteria

A detailed summary of Australian and international odour impact assessment criteria is presented in

Table 11. The criteria illustrate the broad spectrum of odour assessment and regulatory techniques used around the world, and specifically, in relation to the assessment of odour from composting and other waste management related activities.

Table 11: Summary of Australian and international odour impact criteria

Jurisdiction	Odour Impact Criteria		At	F	Protection Level		Reference
	Ct (odour units)	P (%)					
Queensland	0.5	99.5	1 h	1	Wake-free stacks		EHP (2013
	2.5				Ground-level sources and wake-affected stacks		
	1.0				Meat Chicken Farms	Boundary of a non-rural zone	DAFF (2012)
	2.5					Sensitive land use rural zone	
New South Wales	2	99	1 s	a	pop. ≥ 2000	At the nearest existing or likely future offsite	DEC (2006b)
	3				pop. ~500	sensitive receptor based on population	
	4				pop. ~125	density	
	5				pop. ~30		
	6				pop. ~10		
	7				pop. ≤ 2		
South Australia	2	99.9	3 min	b	pop. ≥ 2000	At the nearest existing or likely future offsite	SAEPA (2007a)
	4				pop. ~350	sensitive receptor based on population	
	6				pop. ~60	density	
	8				pop. ~12		
	10				pop. < 12		

Jurisdiction	Odour Impact Criteria		At	F	Protection Level		Reference
	Ct (odour units)	P (%)					
Victoria	1	99.9	3 min	b	At or beyond the fence line		EPA Victoria (2001)
	5				Animal husbandry (at or beyond the fence line)		
Western Australia	2 and 4	99.5 and 99.9	3 min	b	Sensitive receptors		DEP (2002)
Tasmania	2	99.5	1 h	1	At or beyond the fence line		EPA Victoria (2001)
New Zealand	1	99.5c	1 h	1	High sensitivity (unstable to semi unstable		MfE (2003)
	2				High sensitivity (neutral to stable)		
	5				Moderate sensitivity (all conditions)		
	5-10				Low sensitivity (all conditions)		
Austria	1	97	1-5 s	d	Spa areas		OAW (1994)
	1 and 5-8	92 and 97			Residential areas		
Hungary	3-5	e	e	e	Separation distances nearby odour sources		Cseh et al (2010)
Denmark	5-10	99 f	1 min	7.8	Industries	Sensitive receptors	DEPA (2002a)
	5	99 f	1 h	1	Livestock farms	Urban and recreational zones	DEPA (2009)
	7					Conglomeration in a rural zone	
	15					Individual properties	
Norway	1	99 f	1 h	1	Residential areas: at the nearest neighbour		KLIF (2013)

Jurisdiction	Odour Impact Criteria		At	F	Protection Level		Reference
	Ct (odour units)	P (%)					
	2				Industrial areas at the nearest neighbour		
France	5	98	1 h	1	Composting facilities	Sensitive receptors	JORF (2008)
The Netherlands	1.5				Composting of organic waste: new facilities		
	3.0				Composting of organic waste: existing facilities		
	1.5	98			Composting green waste		
	3	99.5					
	6	99.9					
United Kingdom	1.5	98	1 h	1	Most offensive		EA (2011)
	3				Moderately offensive		
	6				Less offensive		
Catalonia, Spain	3	98	1 h	1	Most offensive		DMAV (2005)
	5				Moderately offensive		
	7				Less offensive		
Germany	1	98	1 s	4	Irrelevance criterion		TA-Luft (2002)
		90			Residential and mixed areas		GOAA (2008)
		85			Commercial, industrial, agricultural areas		

Jurisdiction	Odour Impact Criteria		At	F	Protection Level	Reference
	Ct (odour units)	P (%)				
Walloon, Belgium	3	98	1 h	1	Composting facilities: nearest dwellings	Gouvernement wallon (2009)
Quebec, Canada	1 and 5	98 and 99.5	4 min	1.9	Composting and biogas activities: first sensitive receptors	MDDEP (2011) MDDEP (2012)
City of Boucherville, Canada	10 and 5	100 and 98	4 min	1.9	All facilities: first sensitive receptors	Boucherville (2008)
Manitoba, Canada	2	100	3 min	2.3	Residential areas	Manitoba Conservation (2006)
Ontario, Canada	1	99.5	10 min	1.65	Existing facilities: sensitive receptors	Ferguson and Tebbutt (2015)

Source: Selectively reproduced from Brancher et al (2017).

a Fixed peak-to-mean factor (F) are dependent upon the type of source, atmospheric stability and distance downwind.
b No guidelines are provided to determine F for an integration time that deviates from 1-h mean value.
c The baseline P is 99.5th, although 99.9th is also used to assist in the evaluation of model results depending on the type of source and consistency of emission data (MfE,2003).
d Variable: F dynamically depends on the distance from the source and the atmospheric stability (Schauberger et al, 2000, 2013; Piringer et al, 2007, 2014, 2015). In certain circumstances, a constant factor (F=4) used in Germany is adopted.
e No guidelines are provided to P, At and F.
f The maximum monthly 99th percentile should be extracted to verify compliance against the criterion.
g There is no mention of the short-term A_t derived from hourly values by using a F=2.3.
h F depends on the Pasquill-Gifford atmospheric stability classes.

APPENDIX B

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APPENDIX C

Table 12: Review of public Environmental Authorities for known active composting sites in Queensland (source: DES)

EA Number	Operator	ERAs held	Waste types that can be accepted	Conditions aimed at controlling odour emissions
EPPR00211513	AJK Contracting Pty Ltd	ERA 16 ERA 33 ERA 53 ERA 57	The only waste materials permitted to be accepted for composting on the approved site are: a) wood waste (excluding chemically treated timber) including pallets, offcuts, boards, stumps and logs; b) green wastes (including vegetation); c) sawdust; d) vegetable oil wastes and starches; e) biosolids; f) dewatered paper sludge; g) livestock manure; h) dewatered grease trap sludge; i) dewatered fertiliser sludge; j) grease trap waste water; k) fly ash; l) mushroom substrate.	**A2-9**: The release of noxious or offensive odours or any other noxious or offensive airborne contaminants resulting from the activity must not cause a nuisance at any nuisance sensitive or commercial place. **A2-10:** The holder of this approval must undertake all reasonable and practicable measures to minimise odour emissions to the atmosphere from the composting operations. Such measures should include: a) composting windrow forming and turning and compost windrow remixing operations in calm weather conditions where prevailing winds are not blowing in the direction of nuisance sensitive places; b) maintenance of any composting windrows and raw material stockpiles in moist conditions; c) minimisation of the storage time of odorous materials on the site; d) not allowing composting windrows to turn anaerobic; e) minimising the storage time of materials that may turn anaerobic; f) ensuring raw materials and the finished compost product are kept at an oxidised state; g) monitoring and maintaining the optimal Carbon to Nitrogen ratio and;

				h) monitoring and maintaining the optimal temperature in the composting windrows.
EPPR00218413	CCH Group Pty Ltd	ERA 53 ERA 57	The only wastes permitted to be used as feedstocks for compost/soil conditioner manufacture are mill mud/ash/filterpress, sawdust and crusher dust.	**A1:** Odours or airborne contaminants must not cause environmental nuisance to any sensitive or commercial place.
EPPR00243513	Warren W Thatcher	ERA 53 ERA 57	The only wastes accepted are: • green waste • wood waste (exc. • Chemically treated timber) • paper mulch • pine bark • pot ash • coal ash • sewage sludge (exc. Heavy metal contaminated sludge)	**A1:** The release of noxious or offensive odours or any other noxious or offensive airborne contaminants resulting from the activity must not cause a nuisance beyond the boundaries of the premises to which this environmental authority relates
EPPR00417413	Sita (Regional Queensland) Pty Ltd T/A SITA Environmental Solutions	ERA 53	**E3**: The only wastes to be accepted at the premises to which this environmental authority relates for use in the composting activities are: (a) general waste; (b) grease interceptor trap effluent and residues; (c) treatment tank sludges and residues; (d) abattoir effluent; (e) fish processing wastes; (f) food processing wastes; (g) nightsoil; (h) poultry processing wastes; (i) vegetable oils; and	**B1:** In the event of a complaint made to the administering authority (which is neither frivolous or vexatious) about odour generated in carrying out the environmentally relevant activity, and the odour is considered by the administering authority to be an unreasonable release, the holder of this environmental authority must take steps to ensure that odour is no longer an unreasonable release.

			(j) quarantine waste treated by an AQIS approved facility.	
EPPR00459213	Kenneth Lindsay Skerman	ERA 53	N/A	**NS1:** The application and use of composting materials plus the mixing of windrows must be managed so as to keep to a practical minimum the release of noxious or offensive odour from the licensed site to any odour sensitive place. **NS2:** Any solid or liquid compost additives which may cause a noxious or offensive odour at any odour sensitive place should be mixed with other composting materials (such as, sawdust) upon arrival at the licensed site. **NS3:** The application of liquid compost additives should be applied so as to keep to a practical minimum the release of excessive amounts of leachate from the compost stockpiles and windrows which may cause a noxious or offensive odour at any odour sensitive place. Pooling of leachate from the use of liquid additives should be keep to a practical minimum. **NS4:** The settling pond user for the collection of contaminated stormwater and leachate must be maintained so as to keep to a practical minimum the release of a noxious or offensive odour from the licensed site to any odour sensitive place. **NS5:** In the event of a complaint regarding odour that constitutes environmental nuisance being made to the administering authority, the holder of the environmental authority must take all measures to reduce the impact of this odour as well as to investigate measures to

				reduce the likelihood of this odour occurring in the future. All complaints should be recorded as required in condition H1 "Complaint Recording".
EPPR00470013	Canerase Pty Ltd	ERA 16 ERA 33 ERA 53	N/A	**B8**: Notwithstanding any other condition of this development approval no release of contaminants from the place to which this approval relates is to cause a noxious or offensive odour at any nuisance sensitive place **B9:** The registered operator must ensure that loads of chicken manure and other odorous organic materials are covered during transport to and from the place to which this approval relates **B10:** The registered operator must not stockpile raw animal manures on the place to which this approval relates
EPPR00561413	Cleanaway Operations PTY LTD	ERA 53 ERA 56 ERA 57 ERA 58	The only waste accepted for composting activity is organic waste.	**PMA001:** Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place.
EPPR00573913	Veolia Environmental Services (Australia) Pty Ltd	ERA 15 ERA 53 ERA 58 ERA 60 ERA 61	Waste Acceptance for Composting and Soil Conditioner Manufacturing: The only wastes that may be accepted and used for composting and soil conditioner manufacturing at the place to which this approval relates are wastes that are one or more of the following: (a) animal manures, including livestock manure; (b) abattoir treatment tank or treatment pit liquids, solids or sludges; (c) beer; (d) bilge waters;	**Air 9:** Release of Noxious or Offensive Odours: The release of noxious or offensive odours, or any other noxious or offensive airborne contaminants, resulting from the activity to which this approval relates must not cause, or be likely to cause, a nuisance at or beyond the boundary of the approved place. **Air 10:** Reasonable Adjustment of Practices, Procedures or Infrastructure for Resolving Odour Nuisance Complaints: The person undertaking the activity to which this approval relates must investigate, or commission the investigation of, any complaints of

		(e) biosolids; (f) boiler blow down water; (g) coal seam gas drill mud; (h) sawdust, excluding sawdust derived from chemically treated timber; (i) fertiliser and fertiliser washings; (j) filter cake and presses; (k) fish processing waste; (l) food and food scrap waste; (m) food processing waste liquids; (n) food processing treatment tank or treatment pit liquids, solids or sludges; (o) food processing waste solids and dewatered solids; (p) fly ash; (q) grease trap waste including treated grease trap waters and dewatered grease trap sludge; (r) molasses; (s) mushroom substrate waste; (t) paper sludge dewatered; (u) paunch material; (v) plaster board; (w) poultry processing waste; (x) sewage sludge (dewatered); (y) sewage treatment tank or treatment pit liquids, solids or sludges; (z) soil treated by indirect thermal desorption; (aa) sugar and sugar solutions; (bb) vegetable oil wastes and starches; (cc) vegetable waste; (dd) vehicle wash down waters; (ee) water based inks; (ff) water based paints;	nuisance caused by noxious or offensive odours upon receipt, or upon referral of a complaint received by the administering authority and, if those complaints are validated, make reasonable adjustments to processes or equipment to prevent a recurrence of odour nuisance. **Air 11:** Odour Monitoring Obligations: The person undertaking the activity to which this approval relates must, if directed in writing by the administering authority, undertake or commission the undertaking of odour monitoring for contaminants released from the approved place and places relevant to ascertaining the level, nature and source of odour nuisance at the affected premises. **Air 2:** Offensive Odour for Composting and Soil Conditioner Manufacturing Any odorous wastes or materials unloaded at the place to which this approval relates for composting and soil conditioner manufacturing must be — (a) mixed or blended and formed into windrows or biopiles on the same day of receipt at the approved place; or (b) covered with greenwaste or compost on the same day of receipt at the approved place.

			(gg) wood molasses; or (hh) wood waste (such as pallets, offcuts, boards, stumps and logs), excluding chemically treated timber.	
EPPR00627513	Transpacific Industries PTY LTD	ERA 53 ERA 57 ERA 58	**G10:** The only regulated wastes that can be accepted at this place are: - grease trap effluent - hide curing effluent - food processing effluent - paper pulp effluent - vehicle washwaters - abbatoir effluent - low level organically contaminated stormwaters or groundwaters - brewery effluent - septic wastes - carper cleaning washwaters - water blasting washwaters - filter/ion exchange resinbackwash waters	**B8:** Notwithstanding any other condition of this development approval no release of contaminants from the place to which this approval relates is to cause a noxious or offensive odour at any nuisance sensitive place
EPPR00644413	Beaumont (Tivoli) Pty Ltd	ERA 33 ERA 53	The only waste materials permitted to be accepted on the approved site are: - tub ground mulch - green waste - forest mulch - cypress chip - sand - crusher dust - coal ash - paper mulch - chicken manure - cow manure - mushroom compost	**B1**: Release of Noxious or Offensive Odours: The release of noxious or offensive odours, or any other noxious or offensive airborne contaminants, resulting from the activity to which this approval relates must not cause, or be likely to cause, a nuisance at or beyond the boundary of the approved place.

			-grain husks and hulls - gypsum - lime - soil	
EPPR00696713	Nugrow Metro PTY LTD	ERA 53 ERA 55 ERA 58 ERA 61	**2-W1:** Receiving and using the following or waste containing the following in manufacturing composting and soil conditioner products is prohibited: a) Asbestos and asbestos containing materials b) Clinical and related waste c) Foundry sand generated from the casting of non-ferrous metals including brass, bronze, stainless steel or any other metal alloys, combination or alloys d) Foundry waste materials including bag dusts, dross and slags e) Municipal solid waste (excluding segregated compostable organic waste) f) Persistent organic pollutants including polychlorinated biphenyls (PCBs), poly fluorinated organic compounds and polyaromatic Hydrocarbons (PAHs) g) Quarantine/Biosecurity waste h) Waste treated by immobilisation or fixation i) Waste contaminated with glass, metal, plastics (including rigid, light, flexible or film) rubber and coatings j) Waste containing restricted stimulation fluids k) Waste having any of the characteristics contained in List 2: Characteristics of controlled wastes, of Schedule A of the Movement of Controlled Waste NEPM (such as, being flammable or emitting flammable gases, liable to	**1-A1**: Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place

spontaneous combustion, oxidising, containing organic peroxides, poisonous, infectious, corrosive, toxic or giving off toxic gases or being ecotoxic).

2-W3: Wastes can only be accepted and used as feedstock if a risk assessment demonstrates all of the following requirements, unless it is accepted and used as part of a trial program:
1. The waste is homogenous
2. The waste has characteristics or constituents that provide and agronomic or soil conditioning benefit to the finished compost product and does not constitute mere dilution of the waste and its constituents into the product
3. The waste does not have any characteristics or constituents that adversely affect the composting process
4. Potential risks from receiving and handling the waste on the site and use of the final products that include the waste have been identified and determined not to present a risk of causing environmental harm

2 - W12: Regulated waste that is not organic must not be used as feedstock in a ratio of greater than 1 part regulated waste to every 3 parts other material (dry weight)

ERA 58 Regulated waste treatment
3-G1: Regulated waste treatment activities conducted under this environmental authority must not be conducted contrary to any of the

			following limitations: 1. receiving and treating to render the waste or soil non-hazardous or less hazardous must only occur for the waste types using the treatment processes specified below: - Bilge waters contaminated solely with oils and oil emulsions - bioremediation - Oil interceptor waters - bioremediation - Waste waters contaminated solely with oils and oil emulsions - bioremediation - Sludges, such as treatment tank sludges, contaminated solely with petroleum based or animal or vegetable oils or oily emulsions - bioremediation - Soils contaminated with one or more of the following contaminants: hydrocarbons, halogenated organic solvents, halogenated organic compounds, non-chlorinated pesticides and herbicides, nitrogen compounds, metals (mercury, lead, chromium) - bioremediation	
EPPR00711613	TEYS AUSTRALIA MURGON PTY LTD	ERA 25 ERA 39 ERA 53	Only the following waste materials are to be accepted: activated sludge and lime sludge from the Teys Australia Murgon Pty Ltd waste water treatment plant and sawdust that has not been chemically treated	**1-A1**: Odours or airborne contaminants which are noxious or offensive or otherwise unreasonably disruptive to public amenity or safety must not cause environmental nuisance to any sensitive place or commercial place
EPPR00757513	MCCAHILL'S EARTHMOVING & SUPPLIES PTY LTD	ERA 16 ERA 53 ERA 55 ERA 56 ERA 57	Wastes can only be accepted and used as feedstock if a risk assessment demonstrates all of the following requirements: 1. The waste is homogeneous. 2. The waste has characteristics or constituents that provide an agronomic or soil conditioning benefit to the finished compost product, and does	Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place.

		not constitute mere dilution of the waste and its constituents into the product. 3. The waste does not have any characteristics or constituents that adversely affect the composting process. 4. Potential risks from receiving and handling the waste on the site and use of the final products that include the waste have been identified and determined not to present a risk of causing environmental harm. Receiving and using the following or waste containing the following in manufacturing composting and soil conditioner products is prohibited: a) Asbestos and asbestos containing materials b) Clinical and related waste c) Foundry sand generated from the casting of non-ferrous metals including brass, bronze, stainless steel or any other metal alloys, combination or alloys d) Foundry waste materials including bag dusts, dross and slags e) Municipal solid waste (excluding segregated compostable organic waste) f) Persistent organic pollutants including polychlorinated biphenyls (PCBs), poly fluorinated organic compounds and polyaromatic Hydrocarbons (PAHs) g) Quarantine/Biosecurity waste h) Waste treated by immobilisation or fixation i) Waste contaminated with glass, metal, plastics (including rigid, light, flexible or film) rubber and coatings	

		j) Waste containing restricted stimulation fluids k) Waste having any of the characteristics contained in List 2: Characteristics of controlled wastes, of Schedule A of the Movement of Controlled Waste NEPM (such as, being flammable or emitting flammable gases, liable to spontaneous combustion, oxidising, containing organic peroxides, poisonous, infectious, corrosive, toxic or giving off toxic gases or being ecotoxic). Lot 3: Activities under this environmental authority must be conducted in accordance with the following limitations: 1. Only aerobic composting methods may be used to manufacture compost or soil conditioners. 2. Recycling or reprocessing regulated waste under ERA 55(2) must only be conducted by using the waste as a feedstock in manufacturing compost or soil conditioner. 3. The only wastes that are permitted to be used as feedstock in manufacturing compost or soil conditioner are: a) Green waste b) Waste untreated timber c) Animal manure d) Molasses/sugar water e) Stormwater f) Grease trap waste g) Oily water and sludge h) Fertiliser-contaminated wash bay water i) Leachate

			j) Treated and/or activate sludge k) Filter cake from grease traps	
EPPR00768013	KATEK AGRICULTURAL AND HORTICULTURAL PRODUCTS PTY LTD	ERA 53	Activities conducted under this environmental authority must be conducted in accordance with the following limitations: 1. The only waste materials permitted to be accepted are organic waste and worm castings suitable for unrestricted use.	Odours or airborne contaminants must not cause environmental nuisance to any sensitive or commercial place.
EPPR00816413	WOOD MULCHING INDUSTRIES PTY LTD	ERA 33 ERA 53	N/A	Odours or airborne contaminants must not cause environmental nuisance to any sensitive or commercial place.
EPPR00823413	REMONDIS AUSTRALIA PTY LTD	ERA 33 ERA 53 ERA 56 ERA 58 ERA 60	The only regulated waste or other defined waste to be received for storage at the place to which this approval applies and treated and/or reprocessed in the corresponding process(es) are listed below: - Treatment tank sludges and residues - grease interceptor trap sludges and residues - food processing waste - aluminium salt slag including any associated non-metallic product (NMP) - fly ash - soils or treatment plant waste streams contaminated with heavy metals or acidic compounds - soils contaminated with heavy tarry compounds and/or hydrocarbons - batteries	Notwithstanding any other condition of this development approval no release of contaminants from the place is to cause a noxious or offensive odour beyond the boundaries of the place to which this approval applies

EPPR00838113	Hopeman Pty Ltd	ERA 33 ERA 53	The only waste materials permitted to be accepted on the approved site are: - green waste - wood chip - sawdust - livestock manure	Air 9: Release of Noxious or Offensive Odours: The release of noxious or offensive odours, or any other noxious or offensive airborne contaminants, resulting from the activity to which this approval relates must not cause, or be likely to cause, a nuisance at any nuisance sensitive or commercial place Air 10: Reasonable Adjustment of Practices, Procedures or Infrastructure for Resolving Odour Nuisance Complaints: The person undertaking the activity to which this approval relates must investigate, or commission the investigation of, any complaints of nuisance caused by noxious or offensive odours upon receipt, or upon referral of a complaint received by the administering authority and, if those complaints are validated, make reasonable adjustments to processes or equipment to prevent a recurrence of odour nuisance.
EPPR00928513	Foxworth Pty Ltd Celroy Pty Ltd Qlight PTY LTD	ERA 53	The only waste materials permitted to be accepted on the approved site are: - green waste - biosolids (exc. Heavy metal contaminated biosolids) - manure	The release of noxious or offensive odours or any other noxious or offensive airborne contaminants resulting from the activity must not cause a nuisance at any odour sensitive place
EPPR00979913	N Q RESOURCE RECOVERY PTY LTD	ERA 53 ERA 55 ERA 56 ERA 57 ERA 58	N/A	Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place.

EPPR01050513	Westrex Services Pty Ltd	ERA 16 ERA 53 ERA 55 ERA 56 ERA 58 ERA 63	N/A	Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place.
EPPR01322213	NUGROW ROCKHAMPTON PTY LTD	ERA 53 ERA 55 ERA 58 ERA 61 ERA 62	Wastes can only be accepted and used as feedstock if a risk assessment demonstrates all of the following requirements: 1. The waste is homogeneous. 2. The waste has characteristics or constituents that provide an agronomic or soil conditioning benefit to the finished compost product, and does not constitute mere dilution of the waste and its constituents into the product. 3. The waste does not have any characteristics or constituents that adversely affect the composting process. 4. Potential risks from receiving and handling the waste on the site and use of the final products that include the waste have been identified and determined not to present a risk of causing environmental harm. Receiving and using the following or waste containing the following in manufacturing composting and soil conditioner products is prohibited: a) Asbestos and asbestos containing materials b) Clinical and related waste c) Foundry sand generated from the casting of	Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place.

		non-ferrous metals including brass, bronze, stainless steel or any other metal alloys, combination or alloys d) Foundry waste materials including bag dusts, dross and slags e) Municipal solid waste (excluding segregated compostable organic waste) f) Persistent organic pollutants including polychlorinated biphenyls (PCBs), poly fluorinated organic compounds and polyaromatic Hydrocarbons (PAHs) g) Quarantine/Biosecurity waste h) Waste treated by immobilisation or fixation i) Waste contaminated with glass, metal, plastics (including rigid, light, flexible or film) rubber and coatings j) Waste containing restricted stimulation fluids k) Waste having any of the characteristics contained in List 2: Characteristics of controlled wastes, of Schedule A of the Movement of Controlled Waste NEPM (such as, being flammable or emitting flammable gases, liable to spontaneous combustion, oxidising, containing organic peroxides, poisonous, infectious, corrosive, toxic or giving off toxic gases or being ecotoxic). 2-W12: Regulated waste that is not organic must not be used as feedstock in a ratio of greater than 1 part regulated waste to every 3 parts other material (dry weight)	

EPPR01333213	CQ Compost Pty Ltd	ERA 53 ERA 55	**W6:** Wastes can only be accepted and used as feedstock if a risk assessment demonstrates all of the following requirements: 1. The waste is homogeneous. 2. The waste has characteristics or constituents that provide an agronomic or soil conditioning benefit to the finished compost product, and does not constitute mere dilution of the waste and its constituents into the product. 3. The waste does not have any characteristics or constituents that adversely affect the composting process. 4. Potential risks from receiving and handling the waste on the site and use of the final products that include the waste have been identified and determined not to present a risk of causing environmental harm. **W4:** Receiving and using the following or waste containing the following in manufacturing composting and soil conditioner products is prohibited: a) Asbestos and asbestos containing materials b) Clinical and related waste c) Foundry sand generated from the casting of non-ferrous metals including brass, bronze, stainless steel or any other metal alloys, combination or alloys d) Foundry waste materials including bag dusts, dross and slags e) Municipal solid waste (excluding segregated compostable organic waste) f) Persistent organic pollutants including polychlorinated biphenyls (PCBs), poly fluorinated	Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place.

			organic compounds and polyaromatic Hydrocarbons (PAHs) g) Quarantine/Biosecurity waste h) Waste treated by immobilisation or fixation i) Waste contaminated with glass, metal, plastics (including rigid, light, flexible or film) rubber and coatings j) Waste containing restricted stimulation fluids k) Waste having any of the characteristics contained in List 2: Characteristics of controlled wastes, of Schedule A of the Movement of Controlled Waste NEPM (such as, being flammable or emitting flammable gases, liable to spontaneous combustion, oxidising, containing organic peroxides, poisonous, infectious, corrosive, toxic or giving off toxic gases or being ecotoxic). **W9:** Regulated waste that is not organic must not be used as feedstock in a ratio of greater than 1 part regulated waste to every 3 parts other material (dry weight)	
EPPR01422513	Nugrow Roma Pty Ltd	ERA 53 ERA 55 ERA 58	**W6:** Wastes can only be accepted and used as feedstock if a risk assessment demonstrates all of the following requirements: 1. The waste is homogeneous. 2. The waste has characteristics or constituents that provide an agronomic or soil conditioning benefit to the finished compost product, and does not constitute mere dilution of the waste and its constituents into the product. 3. The waste does not have any characteristics or constituents that adversely affect the composting	Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place.

process.
4. Potential risks from receiving and handling the waste on the site and use of the final products that include the waste have been identified and determined not to present a risk of causing environmental harm.

W4: Receiving and using the following or waste containing the following in manufacturing composting and soil conditioner products is prohibited:
a) Asbestos and asbestos containing materials
b) Clinical and related waste
c) Foundry sand generated from the casting of non-ferrous metals including brass, bronze, stainless steel or any other metal alloys, combination or alloys
d) Foundry waste materials including bag dusts, dross and slags
e) Municipal solid waste (excluding segregated compostable organic waste)
f) Persistent organic pollutants including polychlorinated biphenyls (PCBs), poly fluorinated organic compounds and polyaromatic Hydrocarbons (PAHs)
g) Quarantine/Biosecurity waste
h) Waste treated by immobilisation or fixation
i) Waste contaminated with glass, metal, plastics (including rigid, light, flexible or film) rubber and coatings
j) Waste containing restricted stimulation fluids
k) Waste having any of the characteristics contained in List 2: Characteristics of controlled wastes, of Schedule A of the Movement of

			Controlled Waste NEPM (such as, being flammable or emitting flammable gases, liable to spontaneous combustion, oxidising, containing organic peroxides, poisonous, infectious, corrosive, toxic or giving off toxic gases or being ecotoxic). **W9:** Regulated waste that is not organic must not be used as feedstock in a ratio of greater than 1 part regulated waste to every 3 parts other material (dry weight)	
EPPR03194415	NUGROW WESTERN DOWNS PTY LTD	ERA 53 ERA 55 ERA 58	**W6:** Wastes can only be accepted and used as feedstock if a risk assessment demonstrates all of the following requirements: 1. The waste is homogeneous. 2. The waste has characteristics or constituents that provide an agronomic or soil conditioning benefit to the finished compost product, and does not constitute mere dilution of the waste and its constituents into the product. 3. The waste does not have any characteristics or constituents that adversely affect the composting process. 4. Potential risks from receiving and handling the waste on the site and use of the final products that include the waste have been identified and determined not to present a risk of causing environmental harm. **W4:** Receiving and using the following or waste containing the following in manufacturing composting and soil conditioner products is prohibited:	Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place.

a) Asbestos and asbestos containing materials
b) Clinical and related waste
c) Foundry sand generated from the casting of non-ferrous metals including brass, bronze, stainless steel or any other metal alloys, combination or alloys
d) Foundry waste materials including bag dusts, dross and slags
e) Municipal solid waste (excluding segregated compostable organic waste)
f) Persistent organic pollutants including polychlorinated biphenyls (PCBs), poly fluorinated organic compounds and polyaromatic Hydrocarbons (PAHs)
g) Quarantine/Biosecurity waste
h) Waste treated by immobilisation or fixation
i) Waste contaminated with glass, metal, plastics (including rigid, light, flexible or film) rubber and coatings
j) Waste containing restricted stimulation fluids
k) Waste having any of the characteristics contained in List 2: Characteristics of controlled wastes, of Schedule A of the Movement of Controlled Waste NEPM (such as, being flammable or emitting flammable gases, liable to spontaneous combustion, oxidising, containing organic peroxides, poisonous, infectious, corrosive, toxic or giving off toxic gases or being ecotoxic).

W9: Regulated waste that is not organic must not be used as feedstock in a ratio of greater than 1 part regulated waste to every 3 parts other material (dry weight)

EPPR03823216	Australian Prime Fibre Pty Ltd	ERA 33 ERA 53	The only waste materials permitted to be accepted on the approved site are: - sawmill residues (inc. sawdust, bark, wood chip, shavings etc.) - mill mud - cane residues - greenwaste	Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place.
EPPR02748514	Corbet Property Pty Ltd	ERA 33 ERA 47 ERA 53 ERA 57		Odours or airborne contaminants must not cause environmental nuisance to any sensitive place or commercial place.

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